Abstract of a thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

CHANGES IN SOIL STRUCTURE UNDER VARIOUS CROPPING SYSTEMS.

by

C. David Lance.

ABSTRACT.

The percentage volume of soil occupied by pores larger than 100 µm in equivalent diameter (ε_{100}) was used as an index of topsoil structure. The effects of variables on ε_{100} porosity values were examined to give information of use to a conceptual model. It was found that root systems, crop canopies and earthworm burrowing may have an effect on preserving ε_{100} pores, but any effects in changing ε_{100} porosity were small compared with tillage, compaction by traffic, dairy stock treading or slaking and slumping.

It was found that ε_{100} porosity was as well correlated with other topsoil physical properties as total porosity. Since the measurement of ε_{100} porosity shows the relative volume of pores that may be readily exploited by the lateral roots of cereals and grasses it was concluded that ε_{100} porosity is a useful index of topsoil structure.

The effects of various crop species on a silt loam topsoil structure IN CANTERBURY, NEW ZEALAND were examined. Three grass species were used (perennial ryegrass (*Lolium perenne*), Italian ryegrass (*Lolium multiflorum*) and tall fescue (*Festuca arundinacea*), as well as clover (*Trifolium repens*) and wheat (*Triticum aestivum*). Bare fallow treatments were associated with a significant ($p<0.01$) decline in aggregate stability, organic matter and total porosity at 0-2 cm depth. Wheat was associated with an intermediate effect between bare fallow and grasses/clover over the two years of study (1984 & 1985). This effect was thought to be due to the ground cover provided by these plants.

Abstract

In the top 5 cm of soil, ash-free-root-dry-matter weights in the second season at anthesis were significantly lower ($p<0.01$) for wheat than for any of the grasses or the clover. Clover and tall fescue produced the largest root weights at 0-5 cm depth (0.90 and 1.18 t ha^{-1} respectively). It was concluded that the low surface root weight of wheat might be unfavourable in maintaining surface organic matter compared with the grasses or clover.

Populations of earthworms were surveyed in selected silt loam topsoils of Canterbury, New Zealand. It was found that mulching compared with burning cereal residues was associated with higher populations of 2 to 3 times. Direct-drilling compared with regular ploughing was associated with higher populations of 1.5 to 2.5 times. Severe compaction by machinery and dairy cattle treading was associated with lower populations of less than 0.5 times those of comparable uncompacted sites.

Controlled laboratory experiments were conducted to study the burrowing of <u>Aporrectodea caliginosa</u> (Sav) at 15, 10 and 5 ^{o}C. In the homogeneous silt loam topsoil used, it was found that there were significant ($p<0.01$) negative correlations between antecedent bulk density and the rates of burrow formation and soil ingestion by this species. Rate of casting above the soil surface was greatest between bulk densities of 1.1 and 1.4 g cm^{-3} (relative densities of 33 and 73 %).

Key words; soil structure, silt loams, root weights, earthworm populations, earthworm burrowing, <u>Aporrectodea caliginosa</u> (Sav), organic matter, aggregate stability, bulk density, total porosity, ε_{100} porosity.

CHANGES IN SOIL STRUCTURE UNDER VARIOUS CROPPING SYSTEMS.

——||——

A thesis
submitted in partial fulfilment
of the requirements for the degree
of
Doctor of Philosophy
in the
University of Canterbury

by
C. David Lance.

——||——

Lincoln College
1987

PREFACE

As this thesis is submitted for the degree of Doctor of Philosophy, I am taking this opportunity to preface my work with some of my philosophical ideas. The thesis contains many broad considerations which are relevant to the overall subject of soil structure under different management practices.

At present, China, India, the U.S.A. and the U.S.S.R. are together losing 13.6 billion tonnes of soil annually (Saliba, 1985). In terms of our own life spans that soil cannot be regenerated - it is a non-renewable resource (Beckman & Coventry, 1984; Clayton, 1986).

Soil structure is the first index we have of possible future soil losses. The breakdown of soil structure is a loss of physical fertility which is usually reversible (Greenland, 1977). When soil structure is destroyed to the point where erosion occurs an irreversible process begins; why does this matter?

Strutt (1970) and Low (1972) have shown that much soil structure degradation occurs due to lack of consideration for organic matter returns. Soane et al. (1982) have shown that compaction is a serious limitation to crop growth. Both features are consequences of a new economic era that overrides the old traditional principles for decision making on farms. There is pressure from banks for farmers to perform. We have great expectations of economic fortune that the media delivers to us every day. These things mean that many decisions are made to maximise profits on an annual budget basis. The Strutt report (1970) "tried to show the danger of treating the soil so roughly in one or two years for immediate gain that it will be disastrously unresponsive for several years to come". Osborne (1984) cited the phrase "soil mining" to describe the wanton neglect of the needs of the soil in ignorant, exploitative farming systems.

The soil is better regarded as a capital asset than a resource for exploitation (Schumacher, 1973). No good economist would recommend the use of a capital asset unless there was a real chance for improving or at least maintaining that capital. There are some people who sacrifice economic fortune for the peace of mind of knowing that they are improving the natural resource of the soil, rather than consuming it.

I am concerned that the period covering the preceding generation and our generation are going to be labelled by future generations as the age of waste. At present some of our farming practices threaten the chances of future generations to feed themselves from the land. Because I have a conscience about the wasteful character of our high technology society (the western society), I have chosen to try to make the process of food production from the land more sustainable. There is a saying that we do not inherit from our forefathers: we borrow from our children. Maybe we can develop a sound sustainable system of land use that our grandchildren's grandchildren will thank us for.

I hope that this thesis and my extension work subsequent to and consequent of it will help prevent abuse of the invaluable natural resource of the New Zealand Canterbury Plains. I hope it also helps me facilitate the long, productive and sustained use of this resource.

It is necessary that certain features of this thesis are explained at this point. Certain conventions are adhered to. Means followed by standard errors are used throughout this thesis. Units from other work have been recalculated to conform to the units that are shown in the list of symbols. The phrase "percentage points" is used on occasions when a change in percentage value is being expressed. E.g. a change from 30 % to 40 % is a change of 10 percentage points, NOT 10 %. (This is a change of 33 % from the original.)

One feature of the present day is the veritable mountain of literature available to scientists in all disciplines. I have used reviews of sound standing wherever possible and other literature published since those reviews. The number of references cited are slightly fewer than some contemporary works for this reason.

Another feature of this thesis is the absence of an overall discussion. My work has been multi-disciplinary, so the subject matter has been covered topic by topic and discussed and summarised within each subject chapter. The final chapter includes some criticism of the study as a whole and a collation of summaries to meet the objectives set out in Chapter Two.

ACKNOWLEDGEMENTS.

It is with great gratitude that I thank the N.Z. Soil Bureau at Taita for funding the research fellowship which I have held for the last three years. Thanks also go to Jock Churchman, Freeman Cook, Craig Ross, Phil Hart and Polly McColl from the soil bureau for their assistance.

I thank Jeff Reid and Keith Cameron for their patient and constructive supervision of my study, and Professor Swift for his assistant supervision and the many provisions he has made for me as Head of the Soil Science Department.

The research conducted for this study would not have been possible without the discussions I have had with Richard Gibbs. Others not yet mentioned who have contributed to my understanding of the subject of study include Jo Springett (MAF, Palmerston North), Mike Smetham (Plant Science), Glyn Francis (MAF, Lincoln), Don Heffer (Plant Science), Tom Fraser (DSIR, Lincoln), David Painter (Agricultural Engineering), Graham Buchan (Soil Science) and Rob Kemp (Soil Science).

Technical assistance was gratefully received from Rob McPherson, Alan Wise, Owen Wilson, Brandon Hutchison, Margaret Hanson, Dave Shillito, Dave Fowler, Willy Jack, Jerry Meyer, Dick Lowen, Ian Clarke, Huntly Horn, Francis Fox, Alistair Campbell, Chris Dyson, Dick Sedcole, Graham Bourdot, Joanne Symons, Emma binte Shaharudin, Anne Howie, Woo Yin Chow and Henny-Jane Siefkes-Boer.

Many different properties were visited during the course of the study. I thank the following for allowing me onto their properties and for their assistance; Piers Phillips of Cartwheels, Rangiora; Ben McIvor of Stoke Grange, Rangiora; Nes Stephens of Lake View, Leeston; John Smith of Springs Road, Prebbleton; Nigel Jay and Tory Jordan of Tancreds Road, Lincoln; Jack Wildermoth, Ranger of Riccarton Bush, Christchurch; Bob Wyn-Williams and Miles Rea of DSIR, Lincoln; Graham Tate, Tony Whatman and John McCartin, managers of the Mixed Cropping Farm, Lincoln; Hamish McNeil, manager of the Sheep Breeding Unit, Lincoln; Derek Sheen, manager of the Dairy Farm, Lincoln; C.G. Dennis, manager of the Research Farm, Lincoln.

Finally, and most importantly, I thank my mother and father, and the other members of my family, for their unswerving support. Also, my companions in philosophical outlook have been of immeasurable importance to me during this study. I wish to thank Jo Peel, Cate Parker, Chris Price, Richard Gibbs, Michael Krausse, Woo Yin Chow, and Nigel van Dorsser just for sharing their thoughts with me. Thanks also go to Phil Tonkin, Jack Simpson, Alan Wright and many others for their interest and encouragement. I have also been priviledged to receive the generous hospitality of the Reid, Gibbs, Shaharudin and Hanson families. I hope I have made all these dear friends, especially my parents, proud of me.

CONTENTS

List of symbols and abbreviations.

Some of the units in this thesis are not SI units. Units have been chosen so that numbers may be most easily visualised. Some recurrent treatment abbreviations are also included in this list.

a	mathematical constant		
a^{-1}	per annum (year)		
A	area		m^2
A_s	aggregate stability	(relative dry mass)	%
A_v	available water capacity	(relative volume)	% or mm
b	mathematical constant or index		
B_l	burrow length	$cm = 10^{-2} m$	
B_{la}	burrow length activity	$cm\ d^{-1} = 8.64x10^7 m\ s^{-1}$	
B_n	number of earthworm burrows m^{-2}		
C	clay content	(relative dry mass)	%
cm	centimetre (unit of length)	$cm = 10^{-2}\ m$	
d	diameter		
	day (unit of time)	$d = 8.64x10^4\ s$	
DDF	direct-drilled fallow		
DDIR	direct-drilled Italian ryegrass		
DDW	direct-drilled wheat		
ε_{100}	pore space of pores >100 µm diameter	$(cm^3\ cm^{-3})$	%
ε_a	air filled porosity at field capacity	$(cm^3\ cm^{-3})$	%
ε_t	total porosity	$(cm^3\ cm^{-3})$	%
ε_n	same as for E_{100} where n = diameter (µm)		
g	gravitational constant		$9.8\ m\ s^{-2}$
h	hour (unit of time)	$h = 3.6x10^3\ s$	
ha	hectare (unit of area)	$ha = 10^4\ m^2$	
i	infiltration rate	$cm\ h^{-1} = 3.6x10^5\ m\ s^{-1}$	
I	cumulative infiltration		$kg\ m^{-2}$ or m
km	kilometre (unit of length)	$km = 10^3\ m$	
K_{sat}	saturated hydraulic conductivity	$cm\ h^{-1} = 3.6x10^5\ m\ s^{-1}$	
l	length or height		m
LSD	least significant difference		
mg	milligram (unit of mass)	$mg = 10^{-6}\ kg$	
mm	millimetre (unit of length)	$mm = 10^{-3}\ m$	
M_c	organic carbon content	(relative dry mass)	%
M_t	organic matter content	(relative dry mass)	%

n	number		
n_r	count density of roots	$n\ cm^{-2} = 10^{-4}\ n\ m^{-2}$	
p	probability level		
P	pressure	$Pa = N\ m^{-2}$	
PLF	ploughed fallow		
PLIR	ploughed Italian ryegrass		
PLW	ploughed wheat		
q_{om}	organic matter quotient	(relative distribution)	
Q	volume flux (qualified by subscripts)		$m^3\ (m^{-2})\ s^{-1}$
r	radius		
rh	relative humidity	(relative to saturation)	%
R_s	cone penetrometer resistance	$MPa = 10^6\ N\ m^{-2}$	
S	sorptivity		$m\ s^{-0.5}$
	sand content (particles >60 μm)	(relative dry mass)	%
t	tonne (unit of mass)	$t = 10^3\ kg$	
T	temperature		Celsius
V	volume		m^3
W_n	Earthworm population	numbers m^{-2}	
Y	particles <50 μm diameter	(relative dry mass)	%
Z	silt content (particles 2-60 μm)	(relative dry mass)	%
Δ	finite change	dimensionless	
η	viscosity of liquid		$kg\ m\ s^{-1}$
θ_g	gravimetric water content	$kg\ kg^{-1}$	%
θ_v	volumetric water content	$m^3\ m^{-3}$	%
θ_n	θ_v at n bars suction	$m^3\ m^{-3}$	%
μm	micrometer (unit of length)	$\mu m = 10^{-6}\ m$	
π	3.14159		
ψ	matric potential of water	$bar = 10^2\ kg\ m^{-1}\ s^{-2}$	
ρ	density		$kg\ m^{-3}$
ρ_b	dry bulk density	$g\ cm^{-3} = 10^3\ kg\ m^{-3}$	
ρ_p	particle density	$g\ cm^{-3} = 10^3\ kg\ m^{-3}$	
ρ_{rw}	root weight density	$mg\ cm^{-3} = kg\ m^{-3}$	
Σ	summation operator		
^{o}	degree (unit of angle)		
^oC	degree Celsius	Celsius = K - 273.15	

LIST OF TABLES.

LIST OF FIGURES

CHAPTER ONE

SOIL STRUCTURE EFFECTS ON CROP PERFORMANCE.

Plants are dependent upon the soil for water, air, nutrients and anchorage. That dependence begins with the germinating seedling which has to imbibe water and emerge through the soil surface. During above and below ground growth a plant must be able to absorb nutrients plus sufficient water to meet transpiration requirements through its roots, generally in aerobic conditions. To allow this, a soil's structure must balance two important divergent demands: those of drainage to allow aeration and water retention for use by the plant.

Marshall (1962) described soil structure as "the arrangement of the soil particles and of the pores spaces between them". From the plant point of view, soil structure is a system of pores of varying size which may or may not facilitate seedling establishment and root growth. The continuity of pores is as important as the quantity (Greenland, 1977). Further divergent demands of structure are that the pore system should be stable enough to preserve porosity while not being so strong that plant roots cannot enlarge and explore pores within the system.

The coverage of literature in this introduction centres on porosity, the range of pore sizes useful to plants and soil processes, the different functions of pore size groups and processes that alter the nature of porosity. Greenland (1981) stated that " Porosity is undoubtedly the best guide to soil structural condition".

1.1 POROSITY.

Porosity is the proportion of a soil volume that is occupied by gases and liquids, expressed as a fraction or a percentage. This is also known as void space. Porosity may be subdivided into groups by morphology or groups by size. Void or pore morphology has been categorised genetically by Brewer (1964) as shown in Table 1.1.

Table 1.1 Pore morphology classification from Brewer (1964)

Name	Features	Origin
Packing voids	random packing of peds, aggregates and particles often continuous	Cultivated or newly deposited soil.
Vughs	usually discontinuous and irregularly shaped	compression and occlusion of other void types
Vesicles	rounded voids,like bubbles	gaseous pressures
Channels	regular, continuous, often with organic deposits	soil fauna and root activity (biopores)
Chambers	enlarged biopores often continuous with channels	soil fauna
Planes	faces complimentary, fitting or accommodating, cracks and fissures along planes of weakness.	heaving/shrinking from wetting/drying or freezing/thawing

Pore size distribution depends on soil texture, organic matter content, root and soil fauna activity and mechanical history, including cultivations. In particular, change in the quantity and continuity of macropores (pores >60 μm diameter) has been closely linked with change in structural properties and crop performance (Baver _et al._, 1972; Russell, 1973; Russell _et al._, 1975; Greenland, 1977; Soane _et al._ 1982; Osborne, 1984).

Pores larger than 60 μm equivalent diameter are drainage pores under freely-drained field capacity conditions (Reeve et al., 1973; White, 1979). Other authors choose different pore size thresholds for water retention against gravity. Hamblin (1985) used 30 μm diameter, De Leenheer (1971) used 9 μm, and there are other examples of other choices. For this study 60 μm diameter will be used.

Strictly speaking, the relative volume of pores >60 μm diameter is the "air capacity" (ε_a) of a given volume of soil (Thomasson, 1978). "Air-filled pores" usually means those containing air and not water at the time of sampling, or at a given water content.

Workers such as O'Connell (1975) and Glinski & Stepniewski (1985) have concluded that a minimum of 10 % pores >60 μm should be present for successful cropping. Ball (1981) supported this conclusion by relating air capacity values of 8-12% with the minimum air diffusion rate necessary for root growth. Baver and Farnsworth (1940) showed that a decrease in yield and quality of sugar beet occurred when there were less than 10 % air-filled pores in the topsoil at field capacity. An exhaustive list of other crops that require at least 10 % air filled porosity for unimpeded root extension was reviewed by O'Connell (1975).

Working with New Zealand soils, Gibbs (1980) quoted D.S.I.R. assessments of porosity where less than 6% air-filled pores at field capacity and less than 50% total porosity was "low". Davies et al. (1982) stated that "good" structure is 20-30% air-filled pores at field capacity with 60% total porosity, and that poor structure is 5 % or less air-filled pores at field capacity and less than 40 % total porosity.

Thomasson (1978) classified the porosity of the silty and fine loam groups of soil textures as follows in Table 1.2.

Table 1.2 Classification of Soil Structure by Porosity, from Thomasson (1978).

Air-filled or drainage pores (>60 μm)		Available water pores (0.2-60 μm)	
very good	>15%	very good	>20%
good	10-15%	good	15-20%
moderate	5-10%*	moderate	10-15%*
poor	< 5%	poor	5-10%

* Where the sum of air-filled + available water pores is less than 23% then the structure is 'poor'.

Thomasson (1978) doubted whether air-filled porosities at field capacity above 15% were any extra benefit. It should be noted that Thomasson's work for the Soil Survey of England and Wales placed higher emphasis on drainage than water retention. In Canterbury the emphasis tends to be reversed for climatic reasons. This will be shown in Section 3.2.2.

1.2 PORE CONTINUITY

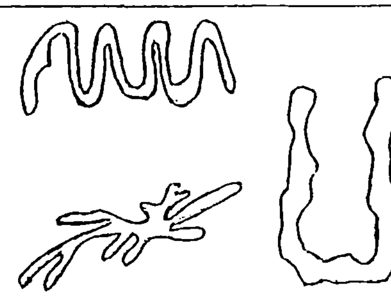
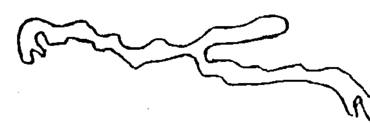
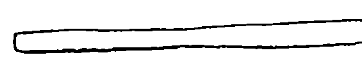
Pore continuity is sometimes measured by direct observation using impregnation techniques. Such techniques have been described by Tippkötter (1983) who studied a subsoil and found that the pore size distribution and morphology closely resembled root size distribution and morphology of wheat and grass. These biopores were 100 to 1000 μm diameter extending from a depth of 1.15 m to 2.15 m. Tippkötter obtained casts of pores >30 μm exhibiting great continuity, and calculated that they were thousands of years old.

Fitzpatrick et al. (1985) have recently demonstrated the difference in pore continuity between poorly ploughed topsoils and direct drilled soils. Using plaster of Paris to impregnate large pores (>2 mm) they showed that ploughing can truncate biopores and smear and compact the plough sole to create a horizon of reduced permeability. In the direct drilled soil, worm and root channels were continuous and extended into the subsoil.

Pagliai et al. (1984) have recently classified pore regularity as shown in Figure 1.1 on a scale from 0.1 to 1. This covers a range from tortuous and irregular pores to regular cylindrical pores. Using thin sections, they also found that under no tillage there was a trend towards pores of smaller size and greater regularity with time compared with frequently cultivated soils.

Tracers have been used by Bouma & Dekker (1978) to observe that large macropores in a clay soil conducted water from the soil surface down their walls under non-saturated conditions. Under saturated conditions an undisturbed soil can conduct water away from the surface

Figure 1.1 Pore regularity classification from Pagliai *et al.* (1984)

Shape-class	Morphology	Display
0.1 - 0.3	very irregular	 strongly digitate U shaped
0.3 - 0.5	moderately irregular	
0.5 - 0.7	moderately regular	
0.7 - 1.0	regular	

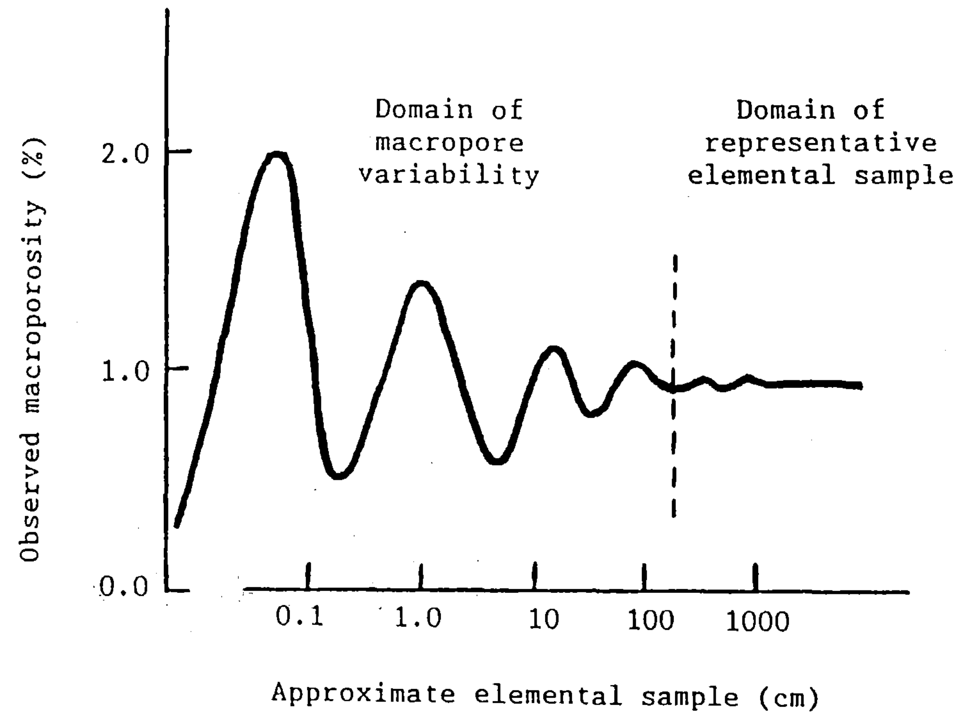
faster than a cultivated soil (Bouma *et al.*, 1975). A similar observation was made by Ehlers (1975) using ultramarine blue in a loess soil and was a conclusion in a review by Bevan and Germann (1982). In Ehlers' work the cultivated soil failed to conduct any blue tracer below the cultivation layer, whereas a soil that was undisturbed for four years transmitted blue dye as deep as 180 cm. This was due to large continuous biopores occupying only 0.2 % of the Ap horizon and 0.8 % of the Bt horizon of the undisturbed soil. Bouma *et al.* (1982) used methylene blue followed by gypsum to impregnate macropores from earthworms in a silt loam. They found that some biopores ending in other conducting channels could conduct water at high rates up to 800 cm h^{-1}.

Omoti & Wild (1979) used fluorescein followed by ultra-violet photography to determine that earthworm channels were more important in conducting water under high rates of water application such as irrigation (5-8 mm h^{-1}). Smaller fissures up to 100 μm were responsible for conducting water under low application rates similar to rainfall (0.7-1.5 mm h^{-1}). They found that 10 % of channels were continuous to 70 cm depth occupying only 0.5 % of soil volume.

White (1985) reviewed work on tracers and macropore flow. He losely defined macropores as those large pores contributing to drainage flow. Working with Escherichia coli, (15 μm in diameter), he showed that preferential flow down macropores occurred in undisturbed soil columns. Disturbance of the soil column much reduced conduction of E. coli, presumably because continuity was interrupted by disturbance.

Infiltration rate and saturated hydraulic conductivity are traditional indicators of pore continuity. The values obtained for such measurements have a distribution reflecting the spatial distribution of macropores as reviewed by Bevan & Germann (1982). A model included in that review showed that a representative elemental (sample size) distance over the soil surface for macropores conducting water was about 1.5 m. This is shown in Figure 1.2.

Figure 1.2 Variability against representative elemental distance for measurements involving macropore conductivity from Bevan & Germann (1982).



Bouma (1982) showed the importance of continuity of pores with the soil surface. He found that cores with macropores continuous with the surface were an order of magnitude more conductive than the same cores attached to the subsoil, and these cores were one or two orders of magnitude more conductive than cores with a surface crust occluding them. Bevan & Germann (1982) found that a small change of 0.002% in macroporosity resulted in a change in conductivity from 6 to 10 cm h^{-1}.

An increase in earthworm channels larger than 1.5 mm under zero tillage compared with regular ploughing was shown by Barnes & Ellis (1979). They found at least twice the number of channels at all depths down to 50 cm. Some undisturbed soils studied by Barnes & Ellis showed numbers of channels four times those of comparable ploughed soils. The earthworm species present could be expected to create biopores to at least 1 m depth (Edwards & Lofty, 1977; Lee, 1985). This will be discussed more fully in Chapter Seven.

Peterson & Dixon (1971) and Hole (1981) calculated and observed that burrows made by soil fauna that have a U-shaped form (see Figure 1.1), with one end higher than the other, are particularly good at conducting water. This is because air can escape from the higher end of the burrow, thus reducing the chance of trapped air that might limit water flow. Such burrows may be formed by deep burrowing lumbricid earthworms originating from Europe (see Chapters Six and Seven).

The question of pore continuity on a field scale, especially biopores, is a very poorly understood aspect of soil physics. None of the authors; Ehlers (1975), Bevan & Germann (1982), Bouma (1982), Bouma et al. (1982) mentioned which species of earthworm created the macropores that they studied. This is unfortunate because different species have their own burrowing habits (Edwards & Lofty, 1977; Bouché, 1975; Lee, 1985) which will be more extensively reviewed in Chapters Six and Seven. The pattern of channelling depends not only on which organism was responsible (plants, earthworms and other fauna), but also on the particular species. There is consequently much work to be done in this area.

1.3 AERATION.

Aeration depends on two major forms of gaseous exchange between the soil atmosphere and the air above the soil, namely mass flow and diffusion. Baver et al. (1972) considered the agents of mass flow and found them to be insignificant under most circumstances compared with diffusion. Most studies have concentrated on rates of diffusion.

The oxygen concentration of soil air should be at least 10 % by volume (partial pressure of 10 kPa), the redox potential above 480 mv and the ethylene concentration below 1 ppm for uninhibited root growth according to Glinski & Stepniewski (1985). A value for oxygen diffusion rate of 3×10^{-7} μg m^{-2} s^{-1} was taken to be the threshold for root growth by Hamblin (1985). Baver et al. (1972) also found that 10 % (v/v) of oxygen was the threshold below which root extension was limited.

Brown et al (1965) showed that oxygen requirements of various crops increased with plant size, temperature, soil disturbance and native organic matter content. This indicated that waterlogged conditions could be tolerated by small plants in cool conditions for longer than larger plants in warm conditions. Moreover, Brown et al. found that the rate of oxygen diffusion was only likely to be a problem in capped soils nearly saturated with water.

Ball (1981) stated that a relative gaseous diffusion rate, D/D_o (where D_o is the rate of diffusion in still air), should be greater than 0.005 in order to prevent the development of anaerobic conditions. This was exceeded in a ploughed silt loam topsoil containing mostly packing voids. The rate was not as high in a comparable direct drilled topsoil when both soils were at a soil water potential of -0.02 bars. The value of this comparison is in doubt since Ball rejected cores containing worm channels. Nevertheless, the difference in matrix air permeability is interesting and did lead to the conclusion that an average of 10% air-filled pores at field capacity is necessary to prevent anaerobic conditions developing in temperate soils.

Aeration of any soil horizon depends on adequate drainage below it, and the absence of an impermeable crust above it (Osborne, 1984). A dense or impermeable subsoil may cause groundwater conditions that waterlog a freely permeable topsoil. This is the case with a cultivation pan (Greenland, 1977; Soane et al., 1982; Osborne, 1984). It is important for topsoils to be drained by continuous macropores at a fast enough rate to cope with incident rainfall. In this way, the onset of anaerobic conditions is avoided and crop rooting is unhindered.

In Canada, Douglas & McKyes (1983) found that a silage corn yield reduction of up to 40 % occurred where there was severe traffic compaction. The resultant anaerobic conditions were thought to have been the cause of the yield reduction.

Bakker & Hidding (1970) found that a puddling event (loss of void space in response to shear and vertical forces) on a soil surface with 7 % air-filled porosity at field capcity reduced the oxygen concentration in that topsoil from 15.2 % to 1.1 %. This demonstrated the importance of pore continuity to the soil surface and the potentially deleterious effects of puddling agents such as stock hooves or traffic when air-filled porosity is below the threshold limit of 10 % at field capacity.. Bakker & Hidding calculated that aeration would be affected by puddling in any soil with less than 10 % air-filled porosity at field capcity.

Dowdell et al. (1979) found that the number of days that oxygen concentration exceeded 10 % (v/v) in the soil atmosphere of a direct drilled clay topsoil were significantly greater than under ploughing. This was true of 15 and 30 cm depths and was explained by the presence of continuous macropores in the direct drilled soil.

Most models for gaseous diffusion concentrate on bimodal porosity, e.g. Bevan & Germann (1982) and Currie (1984). In these models only inter-crumb pores provide pathways for diffusion at high moisture contents. At lower moisture contents inter and intra-crumb pathways are available. This concept was developed from diffusion experiments conducted with homogeneous aggregates rather than intact field cores.

Dutch work reviewed by Cannell (1985) showed that a direct drilled soil allowed greater air diffusion at high moisture contents due to greater large pore continuity. Douglas et al. (1986) found that where cores from minimum tillage soil contained vertically orientated earthworm channels the air permeability was two to four orders of magnitude higher than cores without such pores. There was a close correlation between permeability of pores and their calculated dimensions.

1.4 INFILTRATION RATE AND DRAINAGE.

Rate of water entry into a soil is usually studied in order to predict irrigation acceptance, rainfall acceptance and run-off events. As reviewed by Hillel (1980), there are two major phases for saturated ponded conditions (see Figure 1.3). The first is sorptivity (S) where the profile is becoming saturated with water and then steady state infiltration rate (i). Sorptivity is governed by antecedent moisture content, total porosity and steady state rate. Theoretically steady state depends on the slowest horizon in the profile. A simple equation for cumulative infiltration is as follows (Hillel, 1980);

$$I = S.t^{0.5} + K'.t \qquad (1.1)$$

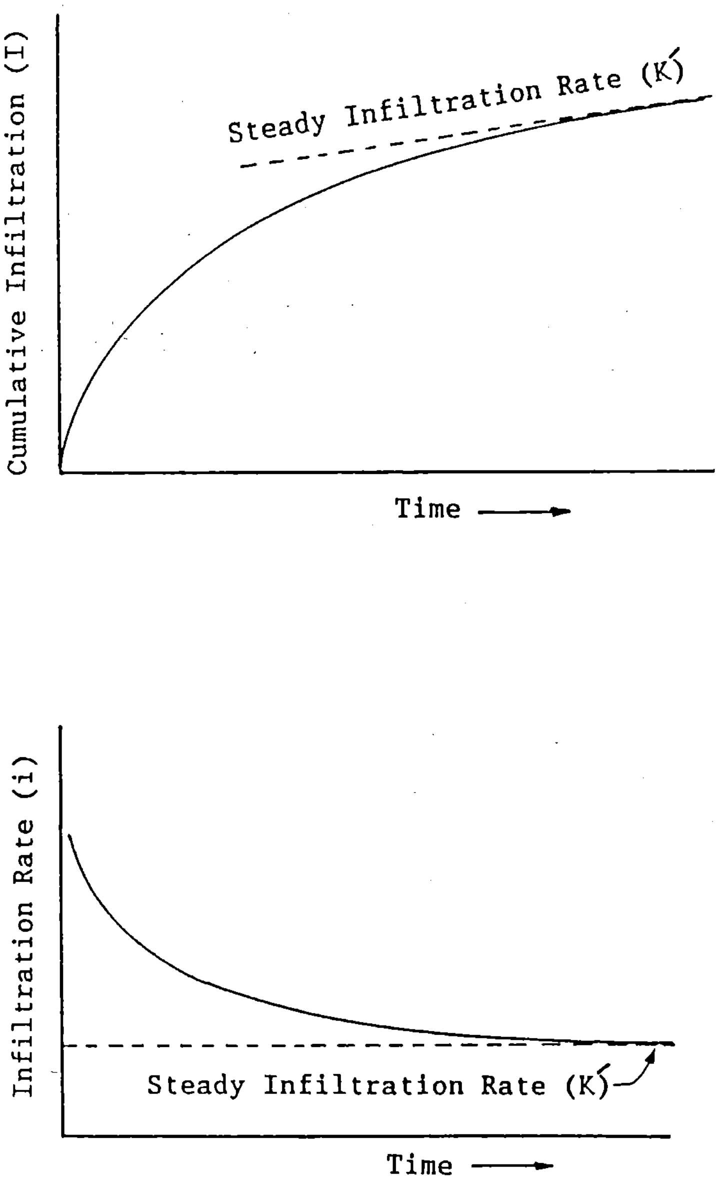
where I is the cumulative infiltration (volume per unit area), S is sorptivity in units of length per time$^{0.5}$, t is time and K' is steady state hydraulic conductivity (length per time).

The differential of this expression (1.1) yields infiltration rate (the slope of the cumulative infiltration curve) as shown in equation 1.2 and Figure 1.3.

$$i = S.t^{-0.5} + K' \qquad (1.2)$$

where i is an infiltration rate tending to K' with time with units of length per time.

Figure 1.3 Cumulative infiltration and infiltration rate against time from Hillel (1980).



As a tool for measuring the water acceptance of a soil surface, infiltration rate has been useful in predicting run-off events (Lull,1959; Hills, 1970) and likely consequent erosion problems (Osborne, 1984; Tarchitzky et al., 1984; Fullen, 1985).

Tarchitzky et al. (1984) used the following equation to model simulated rainfall acceptance during the structural decline of the soil surface to a steady state rate (I_f).

$$i_t = (i_i - i_f).e^{-\gamma pt} + i_f \qquad (1.3)$$

where i_t = infiltration rate at time t, i_i = initial infiltration rate, i_f = final infiltration rate, γ = a soil coefficient related to factors including structural stability, p = rainfall intensity (mm h^{-1}) and t = time from start of rain. Where $i_t < p$, runoff occurs.

To satisfy Darcian flow theory, pores should be evenly distributed in a homogeneous medium, water flow should be laminar and the flux should respond linearly with a change in potential with no reaction between the liquid and the medium, and all resident liquid should be expelled ahead of incoming liquid by piston action at a uniform velocity (White, 1985) according to equation 1.4. Although these conditions are rarely satisfied in the field (Klute, 1982), Darcy's Law is commonly used as a first approximation and was given by Hillel (1980);

$$Q = K.A.\frac{\psi}{l} \qquad (1.4)$$

where Q = volume flux (cm^3 h^{-1}), k = conductivity (cm h^{-1}), A = area of sample (cm^2), ψ = hydraulic potential (cm) and l = length or height of sample (cm).

Choosing a sample size large enough to represent repeating dominant features, namely macropores, is important in achieving a normal distribution of results for statistical analysis (see Figure 1.2). Bertrand (1965), Hills (1970) and Smettem & Collis-George (1985b) experimented with different sized infiltration rate rings and found that the distribution of conductivity values was less positively skew with increasing ring size up to an area of 1 m^2. Working with a heavy clay soil, Bouma (1981) reported that variablity in saturated hydraulic conductivity measurements was considerably reduced by using 10 litre cores compared with smaller cores.

Scotter et al. (1982) compared separate rings, cores and the well method for estimating hydraulic conductivity of profiles. Using two different sized rings gave values an order of magnitude higher than the well method. Cores gave values an order of magnitude higher than the ring method. This was because the cores tended to have large pores that were continuous throughout the cores whereas in the profile biopores only increased conductivity if they short circuited an impermeable horizon to a more permeable one. Cores were also unlikely to contain the limiting horizon in the profile.

Hartge (1984) has recently compared hydraulic conductivity in vertically and horizontally orientated cores taken from a German deep brown earth. He concluded that conductivity was on average lower in a horizontal direction than vertical. However, the distribution of values had similar maximum and minimum limits. The horizontal values had a positively skew distribution and the vertical values were bimodal. As Hartge pointed out, in undisturbed soils with deep burrowing earthworms and unrestricted rooting there is a progressive orientation of pores towards more vertical than horizontal. Under cultivation, particularly ploughing, the orientation of pores is more truly random within the cultivated horizon and so horizontal conductivity can be as great as vertical. Where a plough pan has been generated, far greater horizontal than vertical water movement would be expected.

Whether ploughing of soil improves or decreases infiltration rate compared with direct drilling depends heavily on the experience of the farmer involved. Strutt (1970) stated that one of the disadvantages of direct drilling was lower infiltration rates, while Burch et al. (1984) reported that under direct drilling better infiltration rates and reduced waterlogging had improved wheat yields. Ploughing under optimum conditions may improve infiltration rate if an impervious surface horizon was limiting, whereas in the wrong conditions an impervious plough sole may be generated (Strutt, 1970; Fitzpatrick et al., 1985).

Francis (1986) and Gibbs (1986) have come to similar conclusions about high infiltration rates being accounted for by lateral water movement, even with guard rings. Infiltration rate as an index of soil structure is of little use unless the slowest part of the profile is near the soil surface, or unless the soil has a long history of no mechanical disturbance. Representative elemental area is of secondary consideration to whether infiltration rate is actually measuring vertical water flux or not.

Most soil surveys include drainage as a criterion for describing soil types. In New Zealand the plains soils are grouped by age and then hydrology (Kear et al., 1967) as shown in Table 3.2.3. The factors influencing drainage are either pedological, such as an impervious subsoil horizon, or a groundwater feature dictated by topography and geology.

The water table in a soil is usually determined by rainfall distribution through the year and the saturated hydraulic conductivity of the slowest part of the profile. However, the local hydrology may cause a high water table in a soil that has the potential to drain freely. The position of the water table dictates the drainage class of the soil. From a profile examination, mottling and iron concretions are found in soils that are intermittently waterlogged. A grey gleying of profile horizons usually means permanent, or almost permanent waterlogging (e.g. White, 1979).

The potential drainage property of a soil profile is determined by its texture and its pedological history. The mechanism for drainage is the pore system. White (1985) reviewed current theory on water movement in soil. A derivation from the Poiseuille equation demonstrates the effect of the size of a cylindrical pore on saturated water flow under the influence of gravity (White, 1985);

$$Q_c = \frac{\pi \rho g}{8 \eta} \cdot r^4 \tag{1.5}$$

where Q_c is the volume flux per unit time, r is the pore radius, η is viscosity, ρ is density of the liquid and g is acceleration due to gravity. The equation shows that volume flux is proportional to the fourth power of the pore radius. Examples of the impact of the fourth power relationship can be seen in Table 1.3. Note that the effect on drainage rate (units of height per time) is only related to the square of pore radius.

Table 1.3 Hypothetical flow rates in individual cylindrical macropores and potential flow rates through soil, adapted from White (1985).

Pore diameter (μm)	Draining tension (bars)	Flow rate in one pore ($cm^3\ hr^{-1}$)	Potential drainage in a soil with a fractional pore area of 0.01 (1%) ($cm\ hr^{-1}$).
2000	0.0015	13700	4400
1000	0.003	860	1100
200	0.015	1.37	44
100	0.03	0.086	11

Another approach by Germann & Bevan (1981) gave a theoretical relationship between volume flux through macropores (Q_m) and the fractional area of a horizon occupied by macropores (ε_m). The equation was as follows (Germann & Bevan, 1981);

$$Q_m = \frac{\rho\ g\ A}{\pi\ 8\ \eta\ n} \cdot \varepsilon_m^{\ 2} \tag{1.6}$$

where A is the area of sample containing n macropores.

Smettem & Collis George (1985a) used another simple approach where the major conducting pores were counted and measured per unit area. A volume flux (Q_p) for each major pore was calculated using the following equation (Smettem & Collis George, 1985a);

$$Q_p = a\ .\ r^b \tag{1.7}$$

where a and b are constants for steady state conditions and r is pore radius. Q_p of n macropores was then used to calculate macropore flux (Q_m) in an area (A) by equation 1.8 (Smettem & Collis George, 1985a);

$$Q_m = \frac{1}{A} \cdot \sum_{i=1}^{n} Q_p \qquad (1.8)$$

All of this work goes to show the overriding importance of macropores, especially stable cylindrical biopores, in drainage behaviour. The maintenance of adequate numbers of such biopores is therefore a key element of good soil management.

It is possible to reduce topsoil drainage through a number of pathways. Soil structure reviews (Russell, 1971; Baver et al, 1972; Low, 1973; Greenland, 1977; Davies et al, 1982; Osborne, 1984) tend to cover the same points. Traffic, overstocking and tillage when the soil is too wet to bear the loading imposed are prime causes of compaction, the loss of drainage pores and consequently topsoil drainage. Reduction in drainage increases the chance of run-off and erosion (Tarchitzky et al., 1984) as well as increasing the probability of anaerobic conditions reducing plant growth.

Soane et al. (1982) showed that poor drainage could make tillage or traffic more likely to cause compaction which in turn would further worsen drainage. Traffic has been known to reduce drainage rates by three orders of magnitude (Soane et al., 1982).

Large continuous biopores or macropores have been found to be most important in drainage when they occur. Kneale (1985) observed that in an arable topsoil earthworm channels occupied 2.6 % (v/v) of the core volumes and in the subsoil 0.5 %. These were calculated to be the major conducting pores for drainage.

An impervious zone may occur just below a cultivation depth where there is smearing and compaction (Ehlers, 1975; Fitzpatrick et al., 1985). This may be in the subsoil from ploughing, or in the topsoil from grubbing or ploughing passes. Treading and traffic may also cause impervious platey structures at increasing depths with increasing loads (Soane et al., 1982). Much of these effects can be relieved by a subsoiling pass below the impervious zone once the soil profile has dried out. The efficiency of an artificial drainage system depends on the absence of these impervious zones (Strutt, 1970).

Greenland (1977) emphasised the importance of "lessivage" (blocking subsoil transmission pores by slaked or dispersed particles). This constitutes long term structural damage. Only slow regeneration of transmission pores by root and soil fauna activity is possible below cultivation depth. What most disturbed Greenland was that we are unable to measure such an effect - lessivage is an unquantified process with long term repercussions. The best prevention of this process is to maintain organic matter and lime at levels that prevent slaking or dispersion of the topsoil, and to limit mechanical disturbance to a minimum.

1.5 WATER RETENTION.

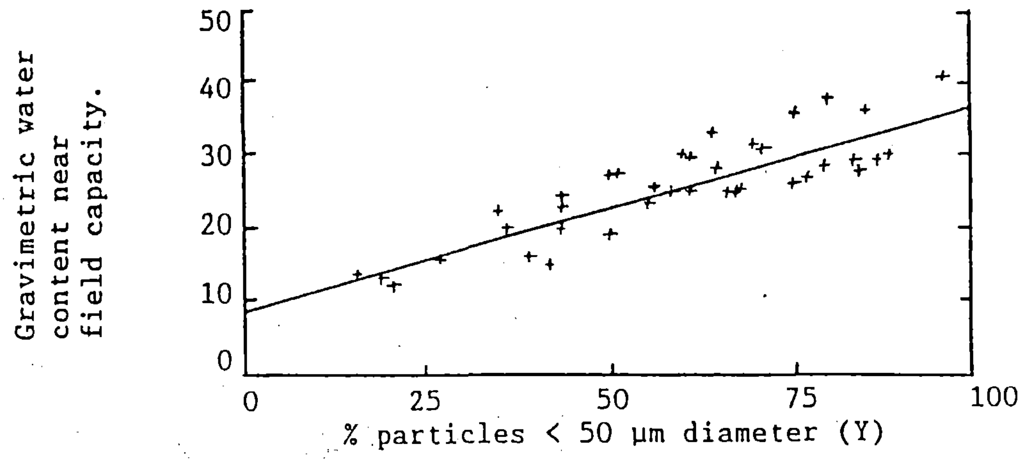
Pores smaller than 60 μm diameter are considered to be those holding water against gravity under free drainage conditions, and most agricultural crops can exploit water held in pores between 60 μm and 0.2 μm (Reeve et al, 1973). There are exceptions to this range of pore sizes (De Leenheer, 1971; Hamblin, 1985). This volumetric quantity is usually known as the Available Water Capacity (AWC or A_v). Broadly speaking this volume is determined by the particle size distribution and organic matter content of a soil (Thomasson, 1978). De Leenheer (1971) even suggested that the porosity which holds available water should be known as "Texture Determined Porosity".

Total retention porosity is the volume of pores smaller than 60 μm, including "unavailable" water in pores smaller than 0.2 μm diameter. This is the same volume as field capacity ($\theta_{0.05}$) under free drainage conditions.

Hall et al., (1977) made an extensive survey of British soils. Most of the variance of total retention porosity ($\theta_{0.05}$) was accounted for by the particle size distribution, especially clay ($p<0.001$). Organic carbon and bulk density also had an effect. The relationship between field capacity volume ($\theta_{0.05}$) and the proportion of particles <50 μm diameter (Y) as derived by O'Connell (1975) is shown in Figure 1.4.

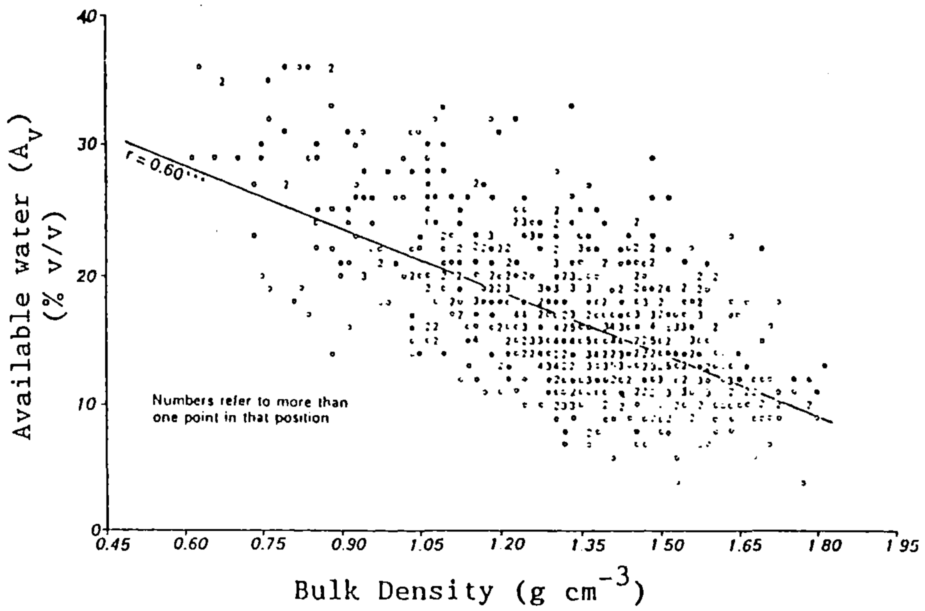
Figure 1.4 Field capacity ($\theta_{0.05}$) against proportion of particles <50 μm diameter (Y) from O'Connell (1975).

$$\theta_{0.05} = 8.93 + 0.2815(Y) \qquad r^2 = 0.74 \qquad (1.9)$$



Hall et al. (1977) found that with a very large number of soils the major predictor of available water capacity was bulk density. Organic matter was also important. This is shown in Figure 1.5.

Figure 1.5 Available water vs bulk density from Hall et al. (1977).



Reeve *et al.* (1973) surveyed 158 British soils with 9 % or less organic matter. AWC (A_v), air capacity (ε_a) and total retention water volume ($\theta_{0.05}$), and the relationship between these properties and clay, silt, and sand content, and bulk density were examined. A summary of the results for topsoils appears in Table 1.4

Table 1.4 Correlation coefficients for porosity values, textures and bulk density of topsoils from Reeve *et al.* (1973).

	Clay	Silt	Sand	Bulk density
Available water (AWC or A_v)	+0.32**	+0.69**	+0.59**	-0.52**
Air Capacity (ε_a)	-0.64**	-0.57**	+0.70**	-0.09
Field Capacity ($\theta_{0.05}$)	+0.74**	-0.76**	-0.88**	-0.46**

Reeve *et al.* used five texture categories which appear in Table 1.5 with their respective available water volumes. These clearly show that the greatest available water capacity occurs in soils with silty textures.

Table 1.5 Texture categories and available water volumes for topsoils from Reeve *et al.* (1973).

Texture	AWC		
Sandy	11.9 %	d	
Coarse Loamy	15.1 %	c	letter NOT shared
Fine Loamy	16.5 %	cb	indicates significant
Clayey	17.4 %	b	difference ($p<0.05$)
Silty	26.0 %	a	

There are instances when AWC has been altered through management. In favourable conditions, reduced or zero tillage tends to result in greater moisture retention than a conventionally cultivated soil (Ellis *et al.*, 1979; Ellis *et al.*, 1982; Hamblin *et al.*, 1982; Osborne, 1984). Pore size distribution is altered in favour of retention pores and a small decrease in total porosity reflects the smaller quantity of drainage pores. When cultivated arable fields are put down to grass for long periods of time, a general increase in porosity is accompanied by an increase in moisture retention (Low, 1972).

Recently, Wood (1985) has reported on soil structure under intensive cultivation and traffic in North Australia for sugar cane. The air-filled porosity at field capacity was preserved by cultivation but water retention porosity declined over 15 years due to cultivation and loss of organic matter.

Obviously there are two different timescales involved (Hall et al., 1977). The work reviewed by Low in 1972 was conducted on long-term cultivation trials of 100 years or more. Over that period, loss of retention porosity occurred, as it did for Wood (1985) over 15 years. For brief events of compaction there is only a loss of large pores and retention porosity remains unaltered or slightly increased by large pores collapsing (Greenland, 1977; Bullock et al., 1985).

Long term reductions in AWC are usually associated with a reduction in organic matter content and a persistent degree of compaction (Low, 1972). Greenland (1977) also associated this condition with 'harsh', angular aggregates which could not be improved by cultivation. The opposite trend is called 'mellowing' and involves the introduction of organic matter into aggregates. This takes many years to occur through natural forces such as swelling and shrinking (Baver et al., 1972), root invasion (Russell, 1971) and earthworm activity (Stockdill and Cossens, 1966; Edwards & Lofty, 1977). A study made by Currie (1966) showed that the porosity of aggregates (which tends to retain water) was highest under permanent pasture and lowest under constant cereals or intensive market gardening.

So far this discussion has concentrated on the available water capacity of a given horizon of soil. By ensuring that unimpeded deep rooting is possible, the available water capacity of the profile as a whole is increased over impeded rooting conditions. The benefit in terms of crop yield of deep rooting was clearly shown in the Manawatu in New Zealand by Evans (1976). Yields and rooting depth for a number of crops are shown in Table 1.6. Lucerne extracted water from the deepest levels (3 m) and produced the greatest weight of dry matter (15.1 t ha^{-1}) over the summer growing season (October to April).

Table 1.6 Total yield from 22nd October to 4th April of different crops in a Karapoti brown sandy loam from Evans (1976).

Crop	Yield (t ha^{-1})	Rooting depth (m)
Lucerne	15.1	3.0
Sorghum	12.3	1.6
Maize	13.1	1.6
Cocksfoot (grass)	12.1	1.4
Perennial ryegrass	4.9	1.4
Perennial ryegrass/clover	6.0	1.4
White clover	5.4	1.4

Evans (1976) also showed that the roots of a perennial ryegrass/clover sward did not penetrate as deeply when the sward was severely defoliated (to 2.5 cm height) on a weekly basis compared with a less severe regime of reducing herbage height to 5 cm whenever it reached 15 cm in length. The dry matter production of the severely defoliated sward was less than half that of the less severely treated sward. This showed that pasture management can also affect dry matter production through depth of rooting and thus water availability.

1.6 SEEDLING EMERGENCE AND SURFACE CONDITION.

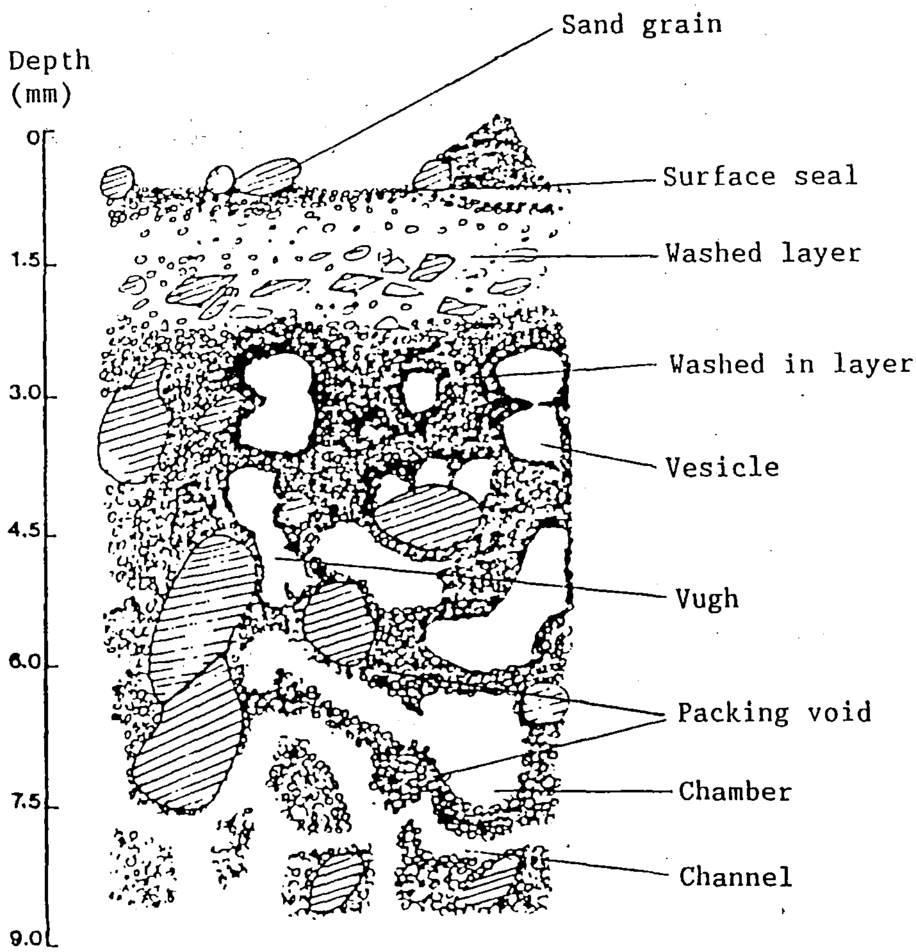
A seedbed of 6 mm diameter aggregates is preferable for most temperate agricultural crops (Osborne, 1984). A harrowing and/or rolling is often required to ensure that seeds are surrounded by and are in contact with soil from which they can imbibe water. Even at moisture contents near permanent wilting point the soil atmosphere has an equilibrium relative humidity of 99% (Scotter, 1976) and seeds will germinate.

The strength of the soil can be too great for a seedling to emerge upwards through the surface, or for the radicle to extend downwards and absorb moisture to support emergence. Any surface crust exceeding 1.5 MPa resistance to the seedling is likely to severely inhibit seedling emergence (Taylor, 1971).

The effect of high resistance is negated by exploitable cracks in a surface crust allowing uninhibited seedling emergence after a horizontal deflection. However, where the crust is uniform, or cracks are too far apart for seedlings to find, then seedlings may fail to emerge (Taylor, 1971). Small seeds such as legumes may only exert a force of 0.15 to 0.6 newtons. Work reviewed by Taylor showed that seed size was highly correlated with median emergence force. Large seedlings such as maize were found to exert a force of 3.8 newtons, but over a greater cotyledon area. Successful emergence thus depends on what force is required to raise a plug of crust material from above the seedling (Taylor, 1971).

Detailed descriptions of the variety of crust morphologies in different soil textures have been given by Tarchitzky et al. (1984) and Collins et al (1986) (see Figure 1.6). Crusts will form more easily on high clay content soils with small aggregates and low organic matter (Baver et al., 1972; Collins et al., 1986). Larger aggregates, greater organic matter and low clay contents tend to prevent crusting. Tarchitzky et al. (1984) found that subsequent erosion due to run off was highest with silty textured soils.

Figure 1.6 Diagram of surface crust morphology of a silt loam from Collins et al. (1986).



To prevent aggregates slaking and dispersing to form surface crusts either they must be protected against rainfall and freezing or they must be water stable (Baver et al., 1972). In this respect, the greater organic matter content in the surface of conservation or zero tillage soils, and the increased probability of some sort of mulch, both contribute to reducing crusting at the soil surface and increasing aggregate stability (Osborne, 1984). Ploughing and working a soil involves exposure of aggregates with lower organic matter contents to rainfall and other forces with an increased chance of capping. Bouma (1982) found that capping of soil could reduce infiltration conductivity by one or two orders of magnitude compared with soil where macropores vented at the surface.

In the special case of direct drilling, new coulter design and techniques for covering seed have been improved by New Zealand workers. A new inverted T-shaped coulter has been shown to be as good as, if not better than, the traditional V-shape seed slot (Baker, 1983). Following a drill with a bar harrow significantly increases seedling emergence (Choudhary & Baker, 1982) due to improved surface mulching and hence better moisture retention around the seed. Preserving a litter mulch may also be important for retaining moisture around an emerging seed (Baver et al., 1972). In 1979, Ellis et al. showed that in a dry autumn emergence of winter wheat can be much more reliable under direct drilling than in a cultivated seedbed due to better moisture retention.

1.7 ROOT IMPEDENCE.

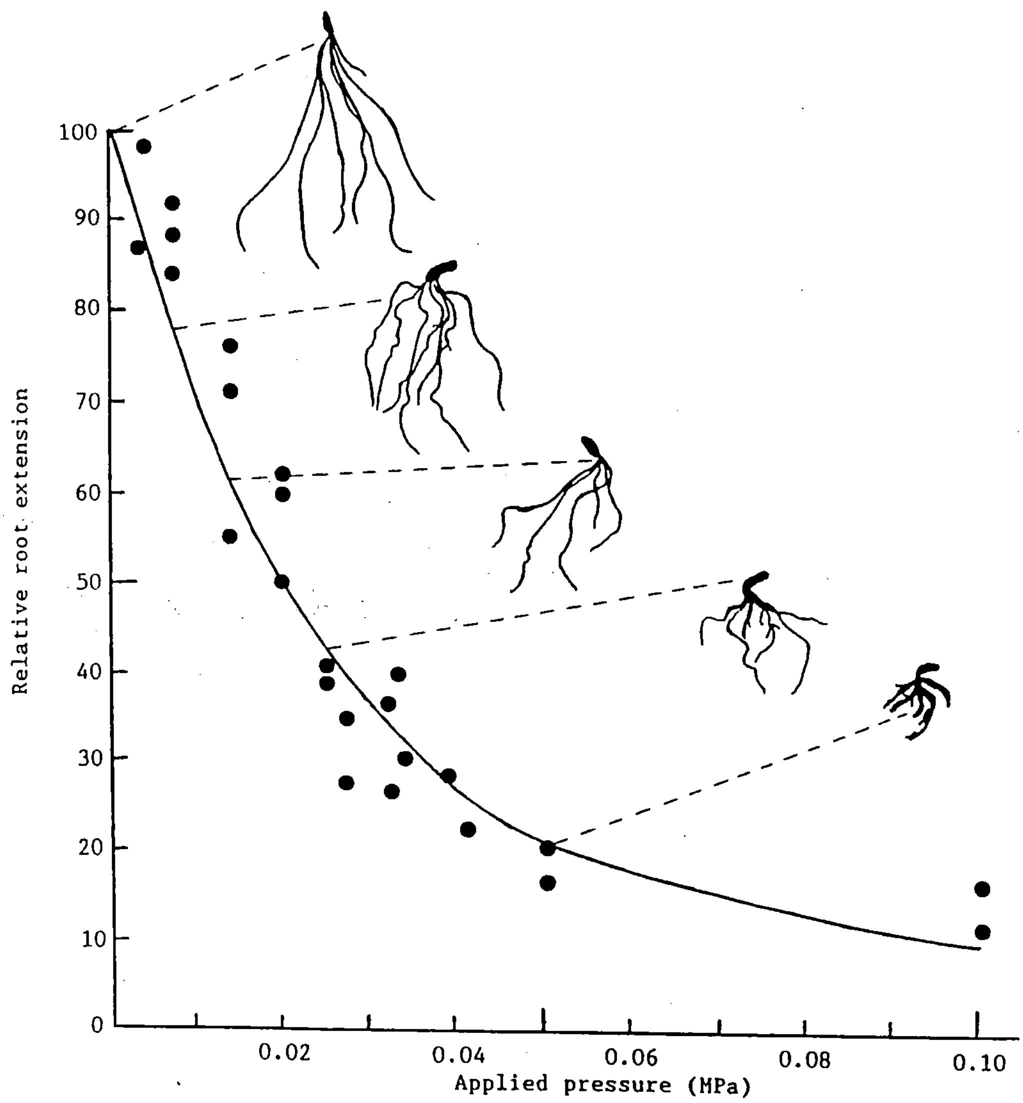
The chief function of roots is to explore an adequate volume or depth of soil to supply enough water and nutrients to maintain the plant above and below ground (Goss & Reid, 1981). Impedence of root extension is only a problem when the plant root system cannot meet the demand for water for evapotranspiration, or when the nutrient supply through roots limits growth.

Greacen (1984) reported that, in artificial laboratory conditions using glass beads, a resistance of 0.05 MPa stopped root extension of a bean. However, in a soil the limiting resistance was 0.4 MPa. Graecen explained this by differences in the viscosity and friction of the different mediums.

Russell *et al.* (1975) used ballotini beads in controlled conditions and imposed different impedence pressures on seminal roots of barley. The relative rates of extension and root morphologies are shown in Figure 1.7.

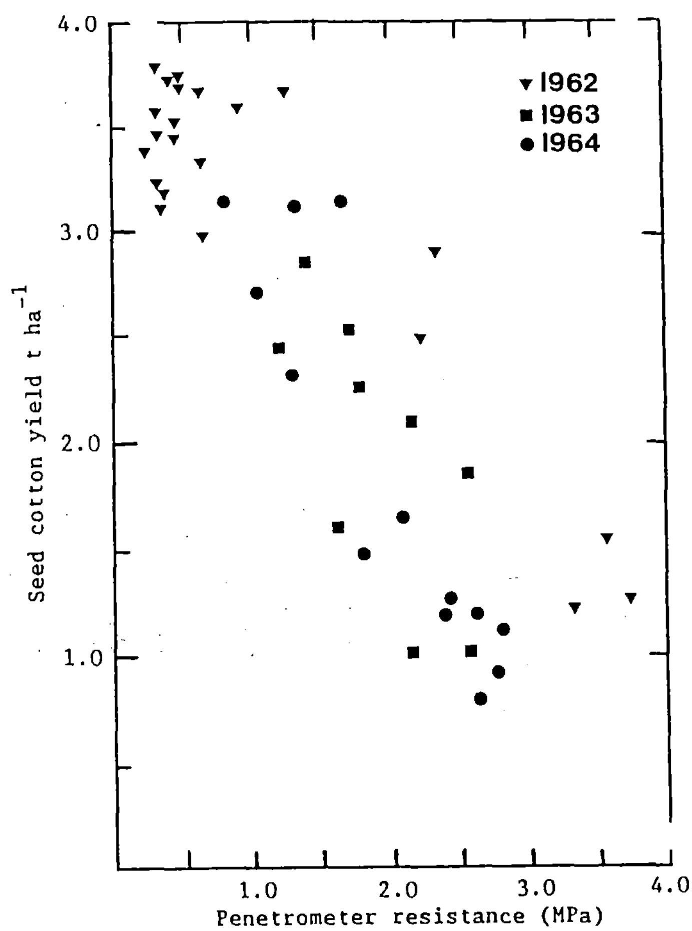
Compensatory ability in plants tends to make cause and effect relationships of soil strength and crop yield difficult to determine. Taylor (1971) cited the work of Carter and Tavernetti (1968) where cotton yield was negatively related to soil strength as determined by a cone penetrometer. This relationship is shown in Figure 1.8. The scatter shows how variable the crop response was to the differences in soil strength over three years.

Figure 7.1 Relative extension rate of barley seminal roots against applied pressure from Russell et al., (1975).



Baver et al., (1972) stated that 0.13 MPa was the resistance that prevented root extension. They also observed that root extension depended on oxygen concentration and water availability as well as soil strength. Both aeration and water extraction are adversely affected by soil compression that causes high physical resistance. This makes the identification of the factor causing root impedance in a given situation difficult, and it is likely to be a combination of factors. Eriksson et al. (1974) used a needle penetrometer to measure a resistance of 1 MPa as being that limiting root elongation.

Figure 1.8 Yield of seed cotton against penetrometer resistance over three years from Carter & Tavernetti (1968).



Hamblin et al. (1982) reported critical Cone Index values of 2.5 to 3.0 MPa for wheat root extension in the field. It may be that given a normal distribution of values about a mean of 2.5 to 3.0 MPa there were enough pores with a resistance of less than 0.05 MPa to allow adequate root extension in Hamblin's work. Ehlers et al. (1983) found that cone indexes of 4.6 to 5.1 MPa did not restrict oat root extension in soils with deep burrowing earthworm channels. They also concluded that water content of a soil was much more important in limiting root extension than bulk density. From their work, it seems that a physical factor to do with orientation of aggregates has to be used to account for the different relationships between bulk density and soil strength (resistance) in a ploughed soil compared with an undisturbed one.

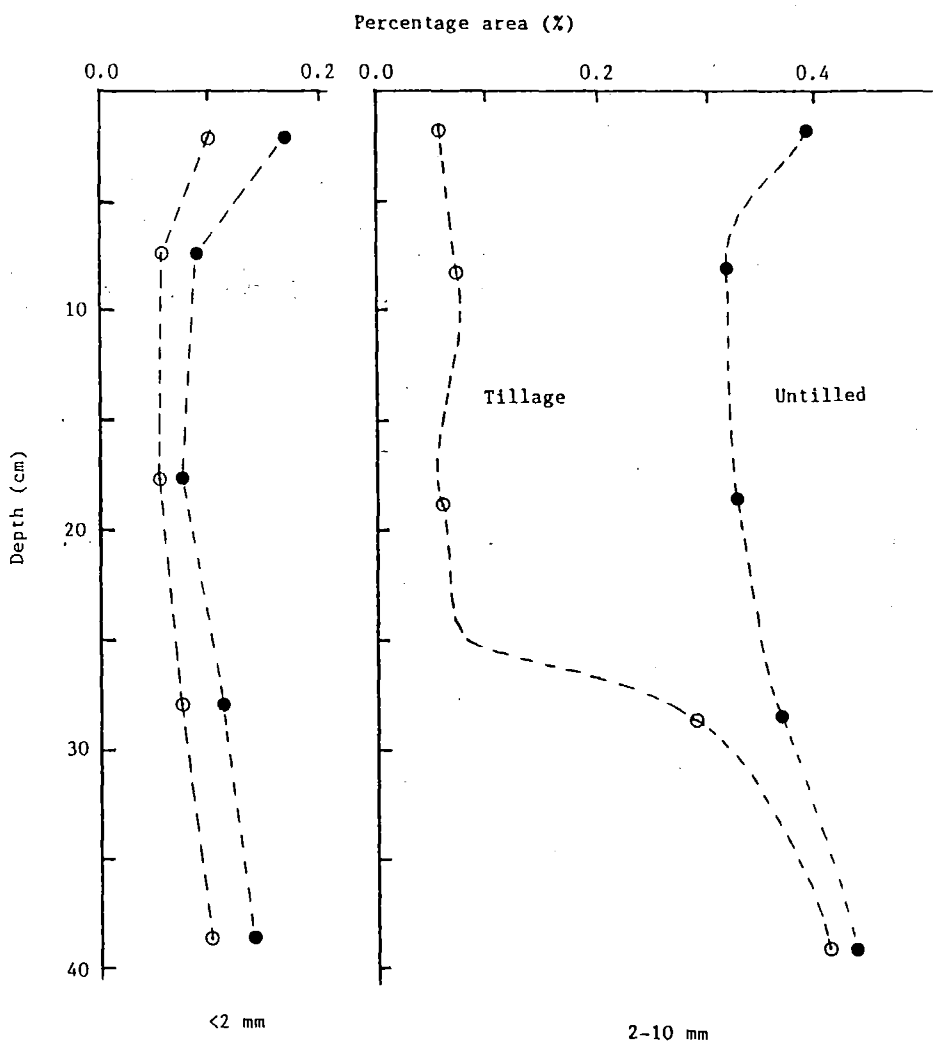
One of the great difficulties with the study of root extension resistance is measuring what the root itself experiences. Wet soils generally exhibit lower strength than dry soils (Baver et al, 1972; Soane et al, 1982). A root tip may be able to take advantage of reduced resistance at a certain time and moisture content which eludes periodic measurement by penetrometer resistance (Batey & Davies, 1971). Cockcroft & Tisdall (1978) found that careful irrigation to maintain water potentials greater than -0.3 bar could maintain penetrometer resistance at less than 0.01 MPa.

Ehlers et al. (1983) found that the area of biopores at a given depth was larger in undisturbed topsoils (see Figure 1.9). This probably meant that roots were able to extend unimpeded well into the subsoil, whatever the cone index of the soil matrix. Ehlers et al. also reported that below 50 cm the majority of roots followed biopores in undisturbed soil. In another study, Finney & Knight (1973) showed that even though a larger proportion of roots was confined to the surface 10 cm under reduced tillage, there was no appreciable difference in yield between reduced and traditional ploughed tillage for winter wheat.

O'Sullivan & Ball (1982) have shown that cone penetrometers are faster and more reliable in measuring soil strength than other instruments. Baver et al., (1972) found that root impedance was better correlated with soil strength than bulk density. Cassel (1982) suggested that specific rather than random sampling approaches should be used for estimating root impedence. Cassel purposely selected areas that were or were not in a tillage row, and were or were not in a traffic line (i.e. subject to wheeling). In this way Cassel found that discing and subsoiling relieved compaction only in the tillage row and not between.

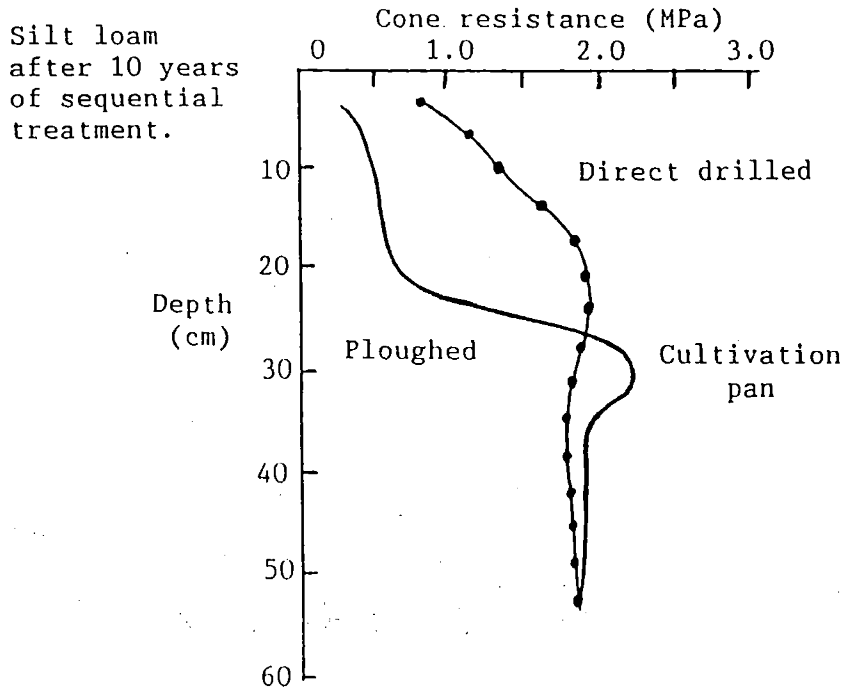
Chisel ploughing, however, caused a more general relief of compaction. This approach to sampling is more informative for root impedence than trying to characterise the whole field with a single value.

Figure 1.9 % Area of biopores <2 mm and 2-10 mm diameter under undisturbed and ploughed conditions with depth from Ehlers et al. (1983).



It is important to note that where a plough pan exists the penetration resistance can exceed that of any part of a direct drilled soil (Cannell, 1985) as shown in Figure 1.10.

Figure 1.10 Cone penetrometer resistance under direct drilled and ploughed conditions with depth from Cannell (1985).



Strutt (1970) concluded that sugar beet, many brassica crops, carrots, spinach, and to a lesser extent peas and beans, were very susceptible to root impedence. Cereals and grasses are less susceptible, but require unimpeded secondary root growth to ensure high yields and even ripening for harvest.

Research is a long way from predicting rooting patterns and adequacy of root extension from soil strength measurements. Thomasson (1978) and Strutt (1970) considered pores larger than 120 µm were those allowing unrestricted root growth. Strutt also pointed out that the pattern of roots in a profile demonstrates the position of pores larger than 120 µm and can be used as a diagnostic tool for soil structure examination. On this basis pores larger than 100 µm equivalent diameter have been studied for this thesis.

1.8 COMPACTION.

The generally accepted definition of compaction is the loss of porosity or increase in bulk density. Soane et al. (1982) have published a comprehensive review of the effects of compaction of soils by agricultural machinery. It is probable that machinery is the major factor causing compaction in the industrialised world (Boekel, 1982). Livestock and natural agents of slumping and shrinking are also important.

The way in which soils of various textures are compacted at different moisture contents by different forces has been reviewed by Terzaghi & Peck (1967) and by Harris (1971). The former workers arrived at the following data (Table 1.7) for maximum compaction of four soil textures (Terzarghi & Peck, 1967);

Table 1.7 Maximum bulk densities of different U.S. textural classes from Terzarghi & Peck (1967).

Sandy clay	2.16 g cm^{-3}	silt (2-60 μm)	1.76 g cm^{-3}
Low plasticity clay	1.92 g cm^{-3}	plastic clay	1.63 g cm^{-3}

Maximum bulk densities not only change with texture but also with organic matter content (van Wijk & Beuving, 1984). These authors made a proposal to facilitate the comparison of degree of compaction between soils of different texture, organic matter content and particle density. They suggested that relative density should be used. To do this a maximum bulk density for a given soil must first be found. Van Wijk & Beuving used a pressure of 1.2 Mpa to maximally compact a soil sample.

The minimum level of compaction was found by pouring dry aggregates into a container. The minimum level was set to zero and the maximum to 100 % or 1.0. Relative density was then calculated from a bulk density value by the following equation (van Wijk & Beuving, 1984);

$$\rho' = \frac{\rho_b - \rho_{min}}{\rho_{max} - \rho_{min}} \times 100 \% \qquad (1.10)$$

where ρ' = relative density, ρ_b = actual bulk density, and ρ_{max} and ρ_{min} are maximum and minimum bulk densities.

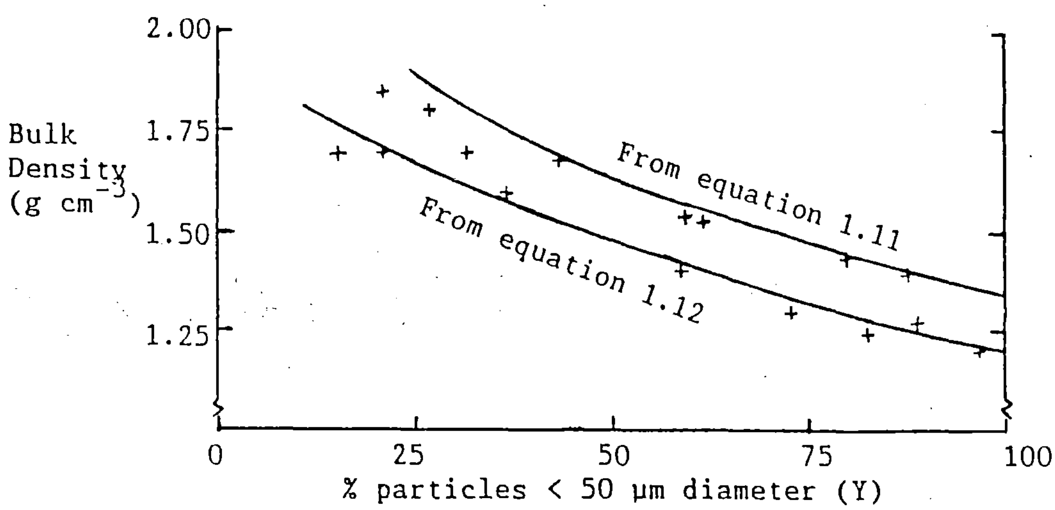
This is a useful tool in field compaction studies. So many reports state bulk densities with no additional data to explain what the values mean. When particle density (or specific density) is also omitted it is not possible to calculate porosity reliably. An extreme example of difficulty with bulk density comparison can be derived from van Wijk & Beuving (1984) when a soil with 40 % organic matter was highly compacted at a bulk density of 0.60 g cm^{-3} and yet a sand with 4 % organic matter may only be at 50 % compaction at 1.60 g cm^{-3}.

Following a survey of British soils, O'Connell (1975) used percentage of particles smaller than 50 μm diameter to predict the bulk densities at which there would be 10 % and zero air-filled pores at field capacity (Figure 1.11). Zero air filled pores was taken to be synonymous with maximum compaction.

Figure 1.11 Bulk density vs % particles <50 μm diameter (Y) showing 10 % air filled and zero air-filled porosity at field capacity from O'Connell (1975).

Saturation at field capacity $\rho_b = \frac{355.6}{Y + 166}$ (1.11)

10 % air space at Field Capacity $\rho_b = \frac{320}{Y + 166}$ (1.12)



Compaction involves rearrangement of primary particles within aggregates and rearrangement of aggregates themselves. The result is a loss of pore space and overall height of the soil surface. Loss in height is approximately proportional to the square root of pressure applied (Harris, 1971).

$$\Delta z = a.P^b \qquad (1.13)$$

where b = 0.5 for most soils, a = constant for soil including factors like moisture, strength, texture, etc.. Δz = sinkage and P = pressure.

The trafficability of a soil has been described by Soane et al (1982) as the ability of a soil to support traffic without structural damage occurring beyond the limits for good crop growth. In many conventional cultivation systems, when a total of 9 passes are made in one season it is possible for only 8 % of a field to remain uncompacted, and on a probability basis 18 % of the area would have had more than four wheel passes and 74 % from one to four passes (Soane et al., 1982). Eriksson et al. (1974) found that on average 4 to 5 times the area of land being cultivated in Sweden had suffered a traffic pass which means that any given area would on average experience 4 or 5 traffic passes.

Raghaven et al. (1978) found that wheat grain yield declined with increasing compaction from 0.84 to 1.30 g cm^{-3} under a variety of traffic treatments on a clay soil. Depth of root proliferation was increasingly shallow with increased compaction. There was also increased variability in both ripening and ease of harvest with increased compaction.

Russell et al. (1975) showed that a compaction event caused a loss of air-filled porosity, especially pores with diameters between 100 and 1200 µm equivalent diameter. These authors pointed out that this size range was the same as the sizes of lateral roots of pasture and cereal species before secondary thickening. They concluded that loss of pores in this size range would be of great importance to root extension. The volume of pores larger than 100 µm (ε_{100}) has been studied for this thesis. Figure 1.12 shows the effect of a compaction event on pores between 100 and 1200 µm diameter. The implications of this will be further discussed in Chapter Two.

Figure 1.12 Porosity values of a soil before and after a compaction event from Russell et al. (1975).

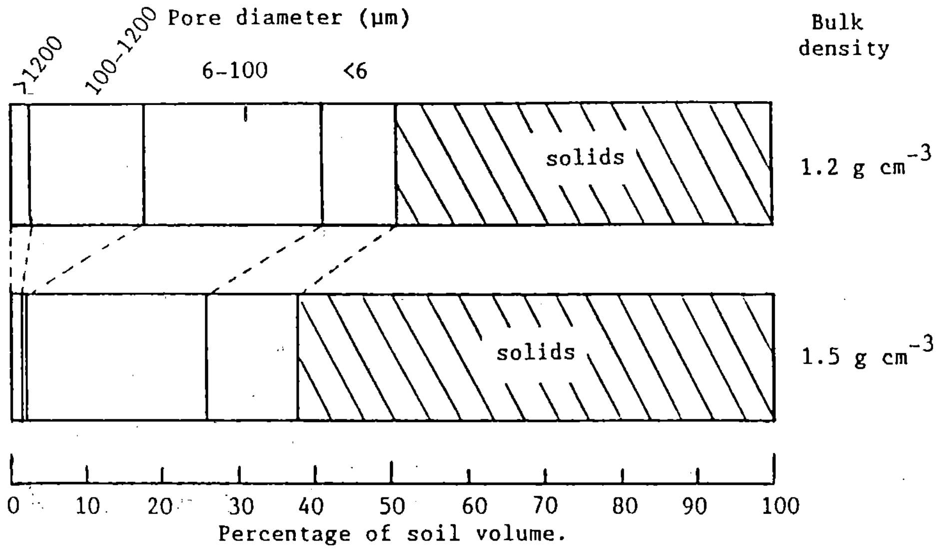
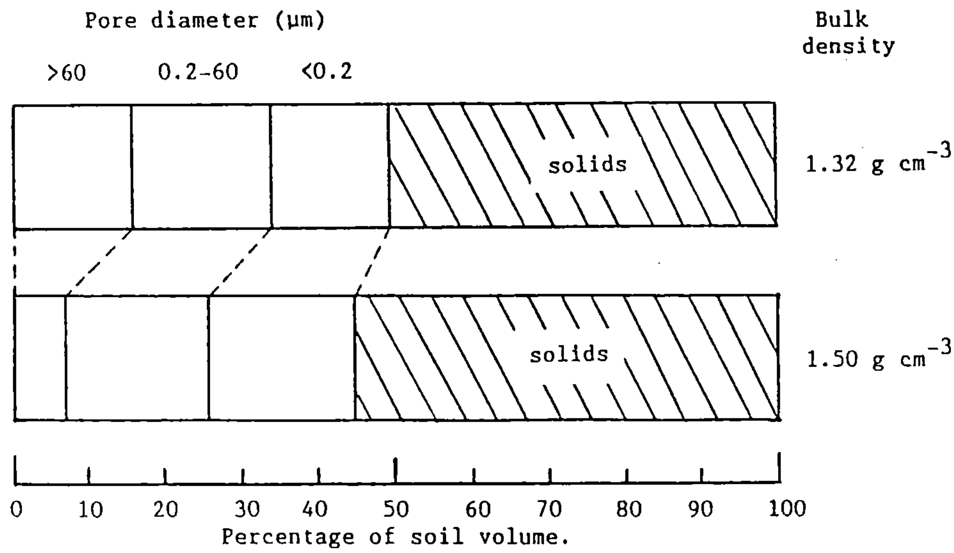


Figure 1.13 Porosity values in the top 5 cm of soil after a compaction event under a loaded vehicle from Bullock et al. (1985).



The work of Bullock _et al._ (1985) showed that it was air capacity rather than available water pores that were lost in a compaction event. This is shown in Figure 1.13 where it may be seen that the "unavailable" water porosity increased under compaction.

Bullock _et al._, (1985) showed that compaction by a loaded vehicle was gradually relieved by swelling during winter months when a bulk density of 1.5 g cm^{-3} (compared with a control of 1.3 g cm^{-3}) occurred. The regeneration of pore space was more rapid in the top 5 cm of this silty clay loam than at lower depths. Rooting was restricted by a density of 1.5 g cm^{-3}, the voids being planar and horizontal between platey peds. Douglas and McKyes (1983) found a 40 % reduction in silage corn yield in a clay soil due to oxygen deficits caused by impeded drainage following 15 vehicle passes with a pressure of 62 kPa per pass.

Soane _et al_ (1982) reviewed a long catalogue of yield losses due to wheeling compaction and highlighted the different demands of crops. In particular, crops such as potatoes, sugar beet, carrots and horticultural bulb crops, where below ground organs are harvested, are sensitive to compaction in terms of yield and quality. Increased use of tramlines, flotation tyres and strip cropping are helping to alleviate the effects of increasingly heavy agricultural machinery (Allmaras & Dowdy, 1985).

Soane _et al._ (1982) stated that the greater the load (rather than pressure) the deeper the compactive effect. Vehicles with a weight of 30 t have caused measurable compactive effects down to 1 m depth on some soils. Soane _et al._ therefore warned that with the increasing mass of agricultural machinery some compaction problems are going to be too deep to be relieved by cultivation or natural forces such as freezing. Such compaction will be long term and as such is better prevented or avoided. The review (Soane et al., 1982) included a recommendation that no axle should be loaded heavily enough to cause compaction below 40 cm depth.

Reduced ground pressure research was reported by Rowse & Goodman (1984) on a sandy loam. A low gound pressure vehicle (30 kPa) was successfully used to drill in near plastic moisture conditions with no deleterious effects to the crop. When a tractor (90 kPa) was used it caused 8 cm ruts and a yield loss.

Treading, or poaching, by animals cannot be ignored. With increasing stock densities, the chances of treading damage are increasing (Greenland, 1977). Dairy cows are the most deleterious of stock since they are large, heavy and frequently herded (Strutt, 1970).

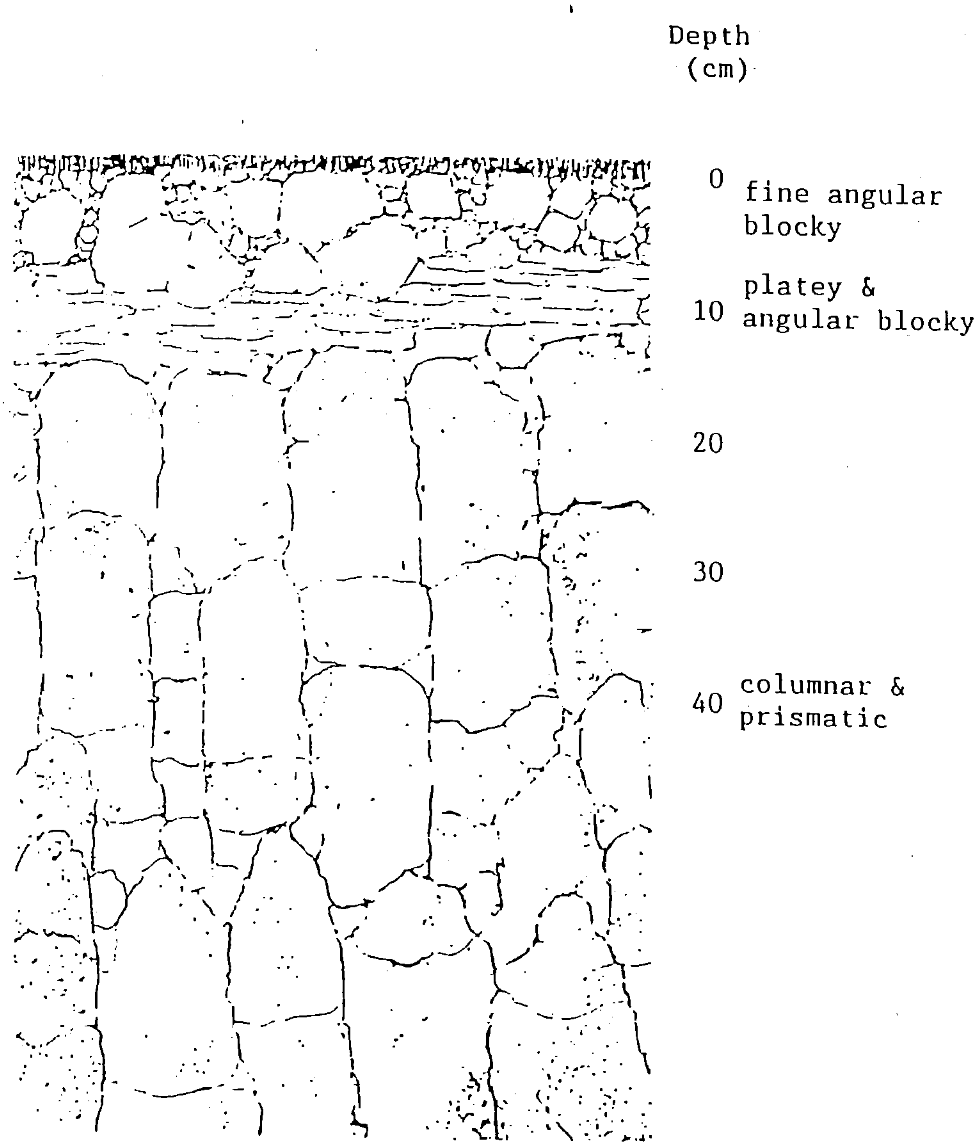
A simulation of a dairy cow hoof was used by Scholefield (1986). A walking cow exerts a pressure of 300 to 400 kPa for about 0.7 second. Compression of the soils used was observed at friable and plastic water contents. At high plastic and liquid water contents liquid flow around the hoof caused puddling and capping. Scholefield (1986) observed that consolidation as well as compaction occurred under treading. Treading is most likely in wet climates or during winter months of drier climates. Compaction zones are frequently at 5 - 10 cm depth from treading (Strutt, 1970) as shown in Figure 1.14. Other British work (Reid & Parkinson, 1984) showed that the 5 - 15 cm depth of a topsoil was the zone worst affected by treading leading to a loss of crumb structure and the development of polygonal peds.

As for retention porosity, there are two timescales for changes in bulk density (Hall et al., 1977). The annual cycle, under cultivation and wetting and drying, may mask a long term decline or increase due to change in organic matter content (Low, 1972; Greenland, 1977).

Eriksson et al. (1974) found that in general 200 kPa was the critical traffic pressure causing compaction. Above this value, soil features would reduce root elongation as shown at 400 and 800 kPa. They also concluded that days when the soil could bear the weight of machinery could be usefully increased by drainage systems, which would help prevent compaction. This Swedish work included an estimate of 8 to 10 % yield losses due to compaction. Eriksson et al. concluded that "In many cases there is no way of supplying machinery with wheel equipment that gives a soil pressure low enough to be acceptable from the point of view of soil compaction".

It should be noted that much of the literature on this subject is from north west Europe and northern U.S.A. where the chances of late harvests and wet cultivations are much higher than the chances of poor soil conditions in Canterbury. It has also not been cost effective to introduce such large machinery into New Zealand cropping as is used in the U.S.A. and north west Europe. Similar climatic conditions to the Canterbury plains are found in south eastern Europe which Soane et al, (1982) considered to be far less at risk from compaction than north west European areas.

Figure 1.14 Treading damage to a profile from Strutt (1970).



1.9 CULTIVATION.

The purpose of cultivation is to modify soil conditions to better suit the crop being grown. There are four major categories of cultivation; soil inversion (ploughing), soil shattering (chisel ploughing, grubbing, harrowing), soil lifting (subsoiling, para-ploughing) and soil compaction (rolling, traffic).

Greenland (1977) pointed out that ploughing is an ancient method for weed control. Since the early 1970s advanced herbicide technology has meant that, as a weed control method, ploughing is less essential (Allmaras & Dowdy, 1985). However, at the same time machinery and energy consumption have become larger (Soane et al., 1982; Larson & Osborne 1971). Ploughing is continued in order to produce an adequate seedbed from land compacted by increasingly heavy machinery.

Since an early edition (1940) of their book, Baver et al. (1972) have advocated that any soil should not be cultivated if it requires more than one pass after ploughing to produce a seedbed. Eriksson et al. (1974) suggested that neither ploughing nor subsoiling should be undertaken unless a net increase in length of pores exploitable by crop roots is generated.

Osborne (1984) advocated that if soils are left alone for long enough, maybe only four years, then zero tillage or direct drilling systems will work on any soil provided they don't have insurmountable inherent problems. This has been demonstrated on a soil that was classified as unfit for direct drilling by Cannell & Ellis (1979), and yet after 10 years Douglas et al., (1986) found that careful management, including drainage, produced a soil that yielded as highly under winter wheat as a conventionally cultivated soil. Positive soil husbandry in areas such as earthworm populations, crop rotations, residue, weed and disease management require new and intensive research to make zero tillage a more reliable system (Janson, 1983; Allmaras & Dowdy, 1985; Cannell, 1985)

Where it has been practised successfully, reduced cultivation has tended to reduce the total pore space of the topsoil compared with ploughing. Earthworm numbers increased and with that pores extending continuously into the subsoil were observed. This in turn caused better infiltration rate, drainage and aeration and deeper root penetration, allowing greater water extraction in dry years (Cannell & Ellis, 1979). The earthworm species present in that British work are not found generally in New Zealand and this topic will be reviewed in chapter six. The same physical effects of direct-drilling due to the occurrence of deep earthworm burrows cannot be assumed to occur in New Zealand.

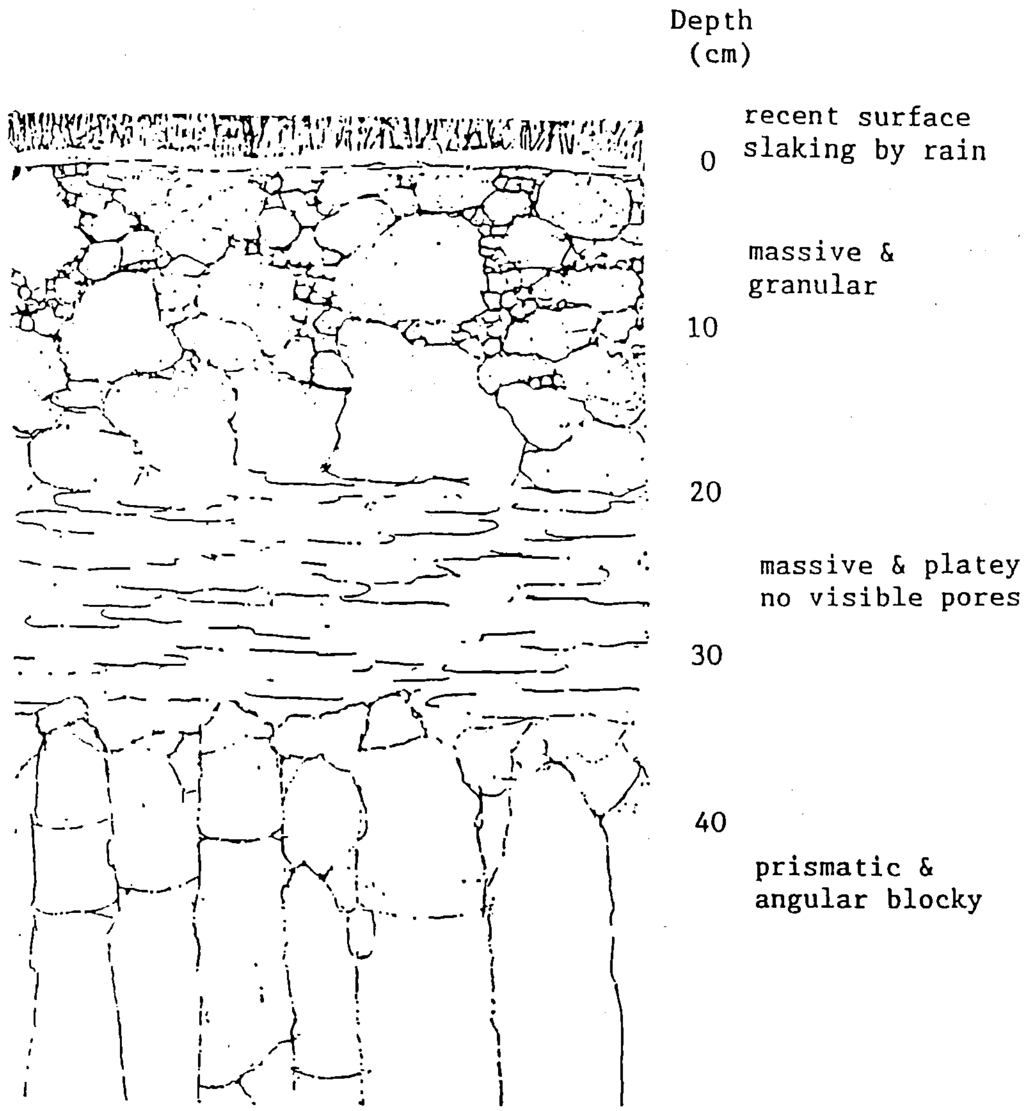
Ellis et al. (1979) and Ellis et al. (1982) have found increases in bulk density, water retention and general soil strength (bearing capacity) under reduced or zero tillage. They have also concluded that variation in yield is far more affected by seasonal weather fluctuations than any essential difference between reduced and traditional cultivations. This view was echoed by Osborne et al. (1978) and Hamblin et al. (1982) from Australia where in a dry year direct drilled wheat outyielded ploughed wheat by exploiting more water in a loamy sand and loamy red earth respectively. Over five or eight years, however, there was little difference between the two cultivation approaches, provided that nitrogen applications were adequate.

The success of cultivations depends on soil conditions when they are practised. Strutt (1970) observed that increased ~~time pressure~~ pressure on the timing of operations occurs as arable farming becomes more intensive. The chances are higher of causing adverse structural conditions through smearing and compaction of plastic soils, or of wasting fuel on dry soils. There has been an economically induced interest in minimum or zero tillage which allows for better timeliness of field operations and a saving in fuel (Larson & Osborne, 1982). Minimum tillage also reduces the chance of creating adverse structural conditions caused by badly timed operations (Greenland, 1977). When the soil is plastic almost any cultivation will damage it (Strutt, 1970). An example of a cultivation pan is shown in Figure 1.15. The adverse effects on the physical properties of the soil have already been stated.

If conservation tillage is not well practiced and traffic is allowed onto the land when the soil bearing strength is too low then compaction will limit yields. Voorhees (1983) found that without cultivation natural relief of compaction below 10 cm was insufficient for successful cropping.

Stringer (1985) found that in the Methven area of Canterbury 79 % of cultivated land is ploughed, grubbed, harrowed and rolled each year. Less than 2 % is direct drilled. Of the remaining 19 %, most is ploughed. Packard & Raeside (1952) observed deterioration in a South Canterbury silt loam under long term wheat/fallow rotation with repeated cultivations and when sown to peas the crop failed. The air-filled porosity was 7 % at field capacity and total porosity was 46 %. By comparison, a relatively undisturbed piece of land adjacent to the site had 18 % air-filled porosity at field capacity and a total porosity of 54 %.

Figure 1.15 Diagram to show cultivation damage in a profile from Strutt (1970).



When compaction has occurred, cultivation is the only rapid means of relieving it (Gibbs, 1986). Sometimes a subsoiling pass is more appropriate than ploughing or grubbing because compaction occurs at or below ploughing depth. As reported above, cultivation usually interferes with the continuity of biopores (Russell, 1971) despite the large increase in packing voids and so the emphasis must be on preventing compaction rather than relieving it (Greenland, 1977).

Structural deterioration resulting from repeated cultivations have been linked with the crops being grown by workers such as Page & Willard (1946) with corn in the U.S.A., Low (1972) for wheat in the U.K. and Cotching _et al._ (1979) in New Zealand with maize on a silt loam. However, if grassland is ploughed, worked and resown every year then a similar but smaller deterioration in structure may be observed compared with growing annual crops continuously (Gibbs, 1986).

1.10 PORE STABILITY

Most workers have concentrated their studies on aggregate stability (Russell, 1971). Reviews such as Kemper & Koch (1966), Harris et al. (1966), Russell (1971) and extensive studies such as that by Chaney and Swift (1984) have established that organic matter, clay, iron and aluminium oxides and calcium carbonate are all factors helping to stabilise aggregates against the forces of rapid wetting by water. Greenland (1977) showed that this sort of test in soils is useful in predicting slaking and dispersal of aggregates and clay in soils which might cause long term damage by blocking transmission pores in subsoils.

Extensive models such as that proposed by Tisdall & Oades (1982) have suggested that aggregation from clay particle sizes upwards involves bacteria and their polysaccharide products, actinomycete and fungal mycelia, and for the largest aggregates crop roots. These agents serve to stabilise aggregates as well as define them. Gasperi-Mago & Troeh (1979) showed that, of the microorganisms involved, fungal species were more effective than actinomycete and bacterial species in inducing stability in an inherently weak fine sandy loam. They further found that this stability improved infiltration rates and resistance to erosion under controlled conditions.

The creation and stabilisation of aggregates also occur by other forces such as wetting and drying, freezing and thawing (Baver et al., 1972; Eriksson et al., 1974; Utomo & Dexter, 1982) and root and soil fauna activity, especially earthworms (Dawson, 1947; Eriksson et al., 1974; Edwards & Lofty, 1977; van Rhee, 1977). Cultivations also create and destroy aggregates, but they do not serve to stabilise aggregates, only to destabilise them (Russell, 1971; Low, 1972). Kemper & Koch (1966) found that cultivated soils containing the same amount of organic matter as undisturbed soils had 5 to 10 % less aggregate stability. This indicates that, quite apart from increasing depletion of organic matter, mechanical disturbance alone reduces aggregate stability. Cultivations sever the structural bonds that naturally occur between soil particles (Baver et al., 1972)

Structural stability is related to particle size distribution. Strutt (1970) stated that soils containing high proportions of sand or silt should not be allowed to contain less than 3 % organic matter in their topsoils. In the same way high clay content soils should contain at least 2 % organic matter. Kemper & Koch (1966) found a large decrease in aggregate stability in soils where organic matter had fallen below 2 %. Greenland (1977) estimated that at least 5 % organic matter should be present in all soils where intensive cultivation was likely in adverse conditions if permanent damage was to be avoided.

Silt soils have a reputation for becoming compacted and organic matter deficient (Strutt, 1970). Thomasson (1978) showed that silt soils are also more intensively used than soils of other textures because of their physical fertility and so are more likely to be abused.

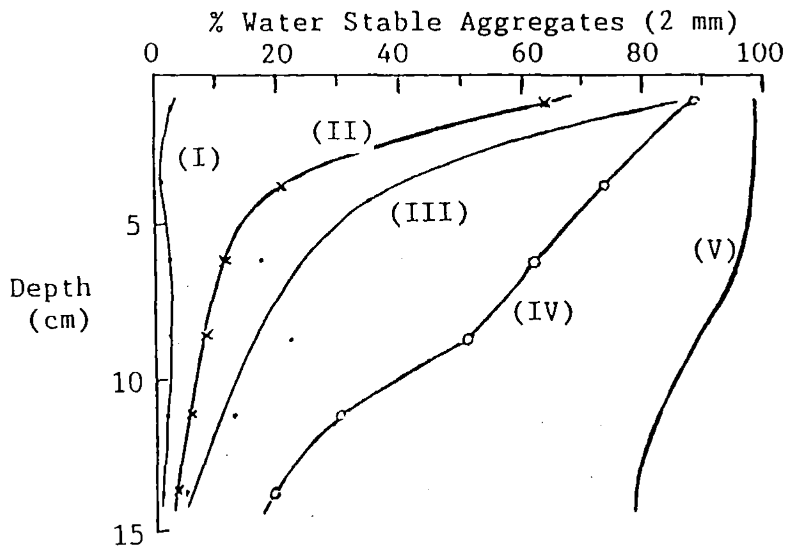
Christensen (1986) showed that organic matter returns, in this case incorporated straw, had a far greater effect in stabilising an inherently weak loamy sand than an inherently more stable sandy clay loam. Christensen also found that the additional organic matter was mostly associated with the silt and coarse clay fraction and that resultant stable aggregates contained a higher concentration of silt than the whole soil.

Organic matter returns and structural stability of agricultural soils are greatest under permanent pasture (Strutt, 1970; Low, 1972; Hall et al., 1977; Douglas & Goss, 1982). Short season annual crops return the least, especially if their management involves burning of residues or harvesting of below ground organs (Russell, 1971; Batey & Davies, 1971). Greater organic matter levels are required to ensure adequate vegetable production in particular (Strutt, 1970).

A few authors have considered the benefits of different pasture species on soil structure (Pavlychenko, 1942; Clement & Williams, 1958; Robinson & Jacques, 1958). Strutt (1970) concluded that perennial ryegrass and clover were amongst the best producers of organic matter and that cocksfoot was also useful. Robinson & Jacques (1958) found that cocksfoot, chewings fescue and perennial ryegrass were useful stabilisers followed by white and red clovers. They also concluded that aggregate formation and stabilisation was greater in species with more ramified root systems. Pavlychenko (1942) used a soil "Binding Equivalent" to assess the contribution different grass roots made to wind erosion resistance. This value was calculated from the tensile strength per unit diameter of root multiplied by the mass of roots.

However, the primary consideration for farmers drilling a ley is palatiblity and stock performance rather than structural improvement (Strutt, 1970). Clement & Williams (1958) concluded that additional organic matter returns from perennial pasture, produced increased surface stabilisation and protected the soil surface from raindrop impact. The major differences are to be found in the surface layers of pasture in the short term. Increases in aggregate stability from organic matter additions further down the profile take many years to accumulate (Greacen, 1958) as shown in Figure 1.16.

Figure 1.16 Aggregate stability with depth for different soil management histories from Greacen (1958).



(I) Continuous cultivation
(II) 3 yr pasture (rye + sub. clover)
(III) 6 yr pasture (rye + sub. clover)
(IV) 10 yr pasture (Phalaris)
(V) Virgin

A decline in organic matter content can be expected due to the overall effect of arable cropping (Low, 1972) including crops such as maize (Page & Willard, 1946; Cotching et al., 1979). However, evidence was presented by Reid & Goss (1982) that the very presence of living roots inhibits the breakdown of native organic matter, although the mechanism for this is still unknown.

Strutt (1970) concluded that, in low rainfall areas of the east of England on easily worked soils, continuous arable farming could be continued. The combination of soil type and climate is the determining factor for management from a soils point of view. As long as organic matter returns are suitable for the soil type and climate any given cropping practice may be chosen. Problems arise when economics dictate decisions unsuitable for soil type and climate, or when unusual weather conditions occur (Greenland, 1977).

Minimum or zero tillage cause a concentration of organic matter at the soil surface (Blevins _et al._,1977) which improves surface stability (Douglas & Goss, 1982; Osborne, 1984) which may in turn allow for longer successful arable cropping before a ley becomes necessary (Strutt, 1970).

What is frequently overlooked is that these aggregate stability studies only extend to prediction of packing void stability. The stability of biopores, already established as those most important for aeration and drainage, has hardly been addressed. Russell (1977) and Hamblin (1985) wrote reviews specifically addressing the stability of the pore system, but they referred mostly to aggregate stability work. Gibbs (1986) used the rate of decline of saturated hydraulic conductivity to characterise the stability of a pore system to water flow.

Lee (1985) stated that deep burrowing earthworm channels might persist for eight years after being vacated. Barnes & Ellis (1979) found that deep earthworm channels persisted for several years in a clay soil despite considerable swelling and shrinking. Since burrows are known to be lined with organic and cast material (van Rhee, 1977; Lee, 1985), and since Dawson (1947) found this material to be much more stable to wetting than surrounding soil, it would seem reasonable to suppose that earthworm channels are very stable pores (Greenland, 1977). This does not seem to have been tested, however.

It would seem reasonable to conclude that since the bearing capacity of the soil increases with bulk density, organic matter content and soil moisture deficit, so too would voids increase in strength, especially biopores.

CHAPTER TWO

OBJECTIVES OF STUDY.

This chapter is concerned with the objectives to be met by this thesis. There follows a brief summary of the literature reviewed in Chapter One. The concept of ε_{100} porosity as an index of soil structure is discussed. A brief discussion of the need for research is given with the reasons for the objectives of this thesis. Finally six objectives of the thesis are detailed.

2.1 INTRODUCTION TO ε_{100} POROSITY.

Several sections in the previous chapter suggested the importance of large continuous pores. The ability of those pores to meet the divergent demands of a growing crop determines the favorability of a soil's structure for crop growth. Those demands are drainage and aeration on the one hand, and water retention for use by the crop on the other.

In particular, the work of Russell *et al.* (1975) showed the importance of pores larger than 100 μm. Figure 1.12 dramatically demonstrated that pores of this size range were those most vulnerable to destruction in a compaction event. The work of both Russell *et al.* (1975) and Tippkötter (1983) showed that pores greater than 100 μm in diameter were those corresponding with the smallest lateral root diameters of grasses and cereals. Strutt (1970) and Thomasson (1978) both concluded that 120 μm was the lower size limit of laterals of grasses and cereals. Therefore, it is not unreasonable to select 100 μm as the lower limit of macropores readily exploitable by crop roots without force being applied by roots to expand pores.

There was conflict of opinion in the literature reviewed in Section 1.5 over pore sizes drained at field capacity. The concept of field capacity only holds for freely drained soils in any case. There is consequently some merit in choosing a pore size range for study on the basis of root diameter, over which there is better consensus in the literature, rather than choosing a disputed pore size range based on drainage.

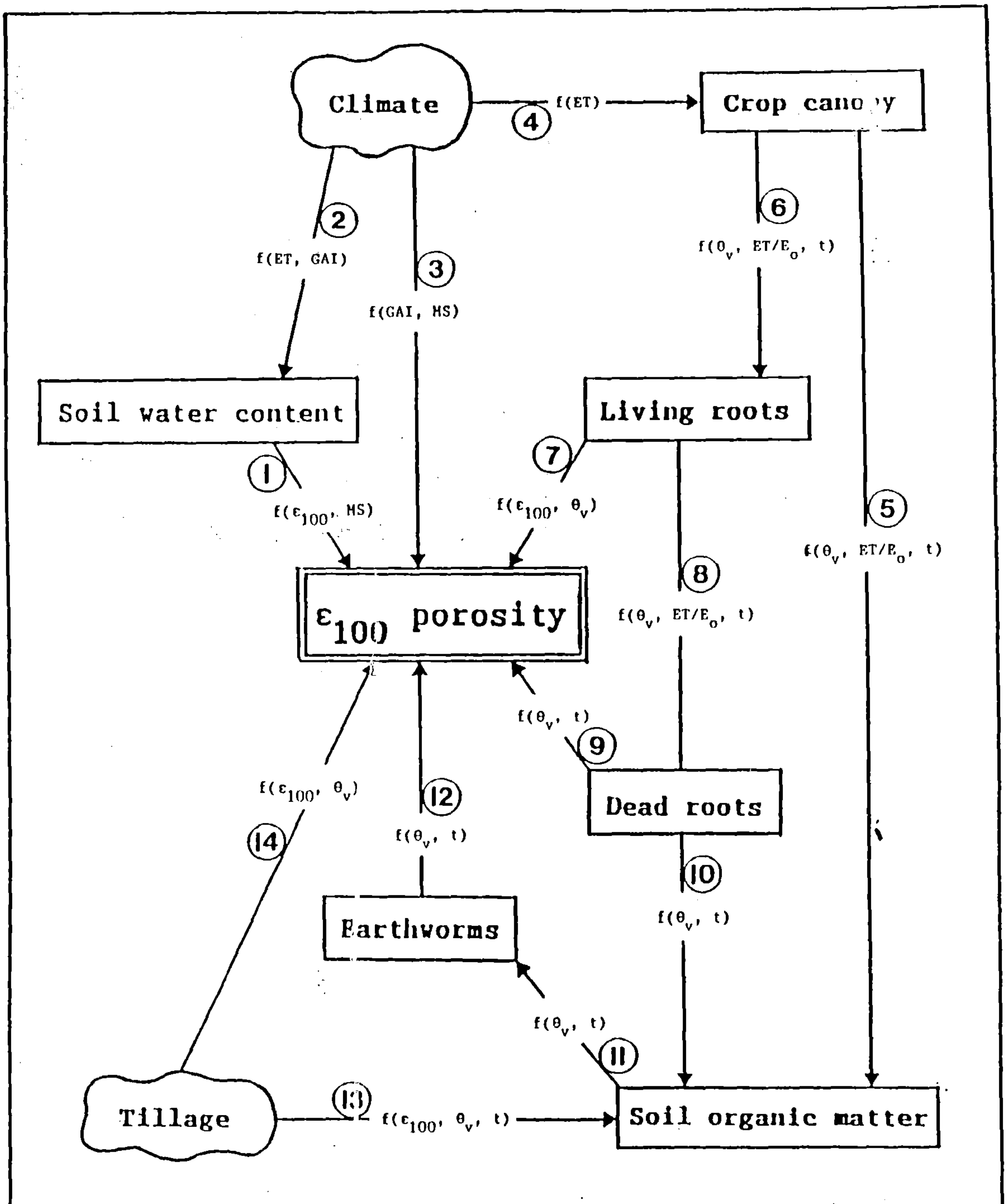
This basis for choice places emphasis on pores exploitable by roots which is a subtley different approach to macroporosity compared with that based on drainage and aeration. It may be that using 100 μm pores as the lower limit will lead to results which better approximate to the way in which plant roots experience soil structure.

For this study, porosity greater than 100 μm in equivalent diameter (ε_{100} porosity) was measured by difference using a tension drainage technique which is outlined in Section 4.4.2. The factors affecting this fraction of porosity are the subject of this thesis.

Gibbs (1986) wrote a Ph.D thesis which was in the same project area as this thesis. He produced a conceptual model with ε_{100} porosity as the central variable. He also presented the hypothesis that ε_{100} porosity was a useful index of topsoil structure. That model is reproduced in Figure 2.1 with slight modification to terminology from the original.

The model in Figure 2.1 has fourteen labelled pathways between variables. On each pathway the functions which principally govern the effect of the original variable on the affected variable are shown. Arrows show the direction of influence from original to affected variables.

Figure 2.1 Conceptual model of changes in structure under different cropping systems from Gibbs (1986).



Meanings of symbols; f = function, ET = actual evapotranspiration (mm d^{-1}), E_o = potential evapotranspiration (mm d^{-1}), GAI = green area index (m^2 m^{-2}), θ_v = volumetric soil water content, ε_{100} = volume of pores >100 μm in diameter (cm^3 cm^{-3}), MS = macropore stability, t = time.

There are notable omissions from Figure 2.1 which were made by Gibbs for simplicity. Temperature was not included as such. Time was considered as developmental time (where temperature above a certain threshold is multiplied by time) or chronological time. In this way, temperature could be conceptually included in the time function if necessary. The concept of macropore stability was included and highlighted the need for a different approach to stability, more towards the functioning of macropores than aggregates. Otherwise, functions mediating the effects of one variable on another are shown to be governed by soil water content, time and antecedent ε_{100} porosity for below ground soil variables. Above ground variables are shown to be mediated by the ratio of potential evapotranspiration to actual evapotranspiration (ET/E_0), soil water content and time. Green area index could be used to calculate ground cover with respect to light interception.

One important assumption that was made by Gibbs (1986) in the presentation of this model was that vertical variability could be ignored if small homogenous increments were used. This assumption will be the subject of some discussion in this thesis, particularly with respect to tillage and organic matter.

Of the variables that are considered in this thesis, tillage requires some further explanation. This variable was exclusive of treading and traffic compaction in the work of Gibbs (1986). However, for this thesis, the important factors of treading and traffic compaction are considered under the umbrella variable of "tillage", as well as the actions of draft machinery which are more usually considered to be tillage.

By focussing attention on changes in ε_{100} porosity, Gibbs showed that research could be orientated to give clear information about the relationships of one variable with another. Thus orientated, research might better predict the effects of the variables being tested upon root growth of grasses and cereals. The particular areas of research for this thesis are given in the next section.

2.2 THE NEED FOR RESEARCH.

Gibbs (1986) examined pathways 7, 8, 9 and 10 of Figure 2.1 in some detail. Consideration was also given to pathways 4, 5, 6 and 14. This thesis is, in part, complimentary to that of Gibbs. Study for my thesis is intended to include detailed examination of pathways 11, 12, 13 and 14, with consideration of pathways 3, 5, 6 and 7. The general concepts embodied in the model are also to be evaluated, especially the use of ε_{100} porosity as an index of topsoil structure.

There is a need to determine the effects of different species on soil organic matter returns, and the distribution of those returns in the soil profile. Literature reviewed in Section 5.1.1 will show this. It is intended to give more information about pathways 8 and 10, combined. Other information can be found simultaneously from a carefully designed experiment concerning pathways 3 and 5. The literature regarding the effects of different crops on organic matter returns is more fully examined in Chapter Five. This sort of research is necessary for producing information on which to base recommendations for changes in crop rotations with regard to soil structure.

In Figure 2.1, pathway 11 shows the effect of soil organic matter on earthworm populations and their behaviour, which is modified by soil water content and time. This pathway must be well understood in order to predict pathway 12, which is the effect of earthworm burrowing on ε_{100} porosity. It is necessary to study differences in earthworm populations and to investigate the effect of organic matter on those populations. It is also important to determine whether organic matter is the only variable in the model that determines earthworm populations.

More specific information is needed to understand pathway 12, the effect of earthworms on ε_{100} porosity. An attempt must be made to carefully quantify the effects of earthworm populations on soil structure, especially ε_{100} porosity. Two of the major reviews on earthworms (Edwards & Lofty, 1977; Lee, 1985) showed that information is still highly qualitative regarding the effects of earthworms on soil structure. This area needs more study.

There is a need in any study to be aware of the full range of values of any given variable. This helps the worker to understand the significance and perspective of any given value of a variable. In order to achieve some perspective for the results of experiments in this study, it will be necessary to collect data from a variety of sources to show possible variation in variable values. Special attention must be paid to the evaluation of ε_{100} porosity as a variable if it is to be useful as an index of soil structure.

For ease of interpretation of results, it is desirable to confine study for this thesis to a selected textural type of soil. To this end, only silt loams and silty clay loams have been selected.

2.3 OBJECTIVES OF STUDY FOR THIS THESIS.

The six objectives of this thesis appear below;

1. To identify and examine the effects of biotic, mechanical and climatic change agents in topsoil structure of Canterbury plains silt loams, with special reference to the model in Figure 2.1.

2. To isolate and quantify the effects of different pasture species and wheat on topsoil structure of a silt loam in the field.

3. To examine and identify earthworm species, their distribution and their population differences in a range of silt loam soils.

4. To quantify and evaluate the effects of earthworm burrowing on silt loam topsoil structure at different antecedent bulk densities under controlled conditions.

5. To survey a range of silt loam topsoils using a number of measurements to evaluate ε_{100} porosity as an index of topsoil structure.

6. To collate the effects of different change agents on soil structure in order to produce recommendations of use to Canterbury farmers on silt loam soils.

CHAPTER THREE

CANTERBURY PLAINS CLIMATE, SOILS AND LAND USE.

This chapter is intended to introduce and place in context the area studied for this thesis. To achieve an understanding of the Canterbury Plains situation, relevant details of the climate and the soils and their origin are included with comments which will aid the interpretation of results later in this thesis. Much of the information given in this chapter is referred to in discussion of results.

A sketch of the history of land use and the present trends in land use are also presented. The trends in soil use are of particular importance to the justification of the research undertaken for this thesis.

3.1 CANTERBURY PLAINS CLIMATE.

The area known as the Canterbury Plains extends from Amberly in the north to Timaru in the south (see Figure 3.1). From the east coast, the plains extend inland to the foot-hills of the Southern Alps at Oxford, Methven and Fairlie. This area is about 760 000 ha of productive agricultural land of great importance to New Zealand.

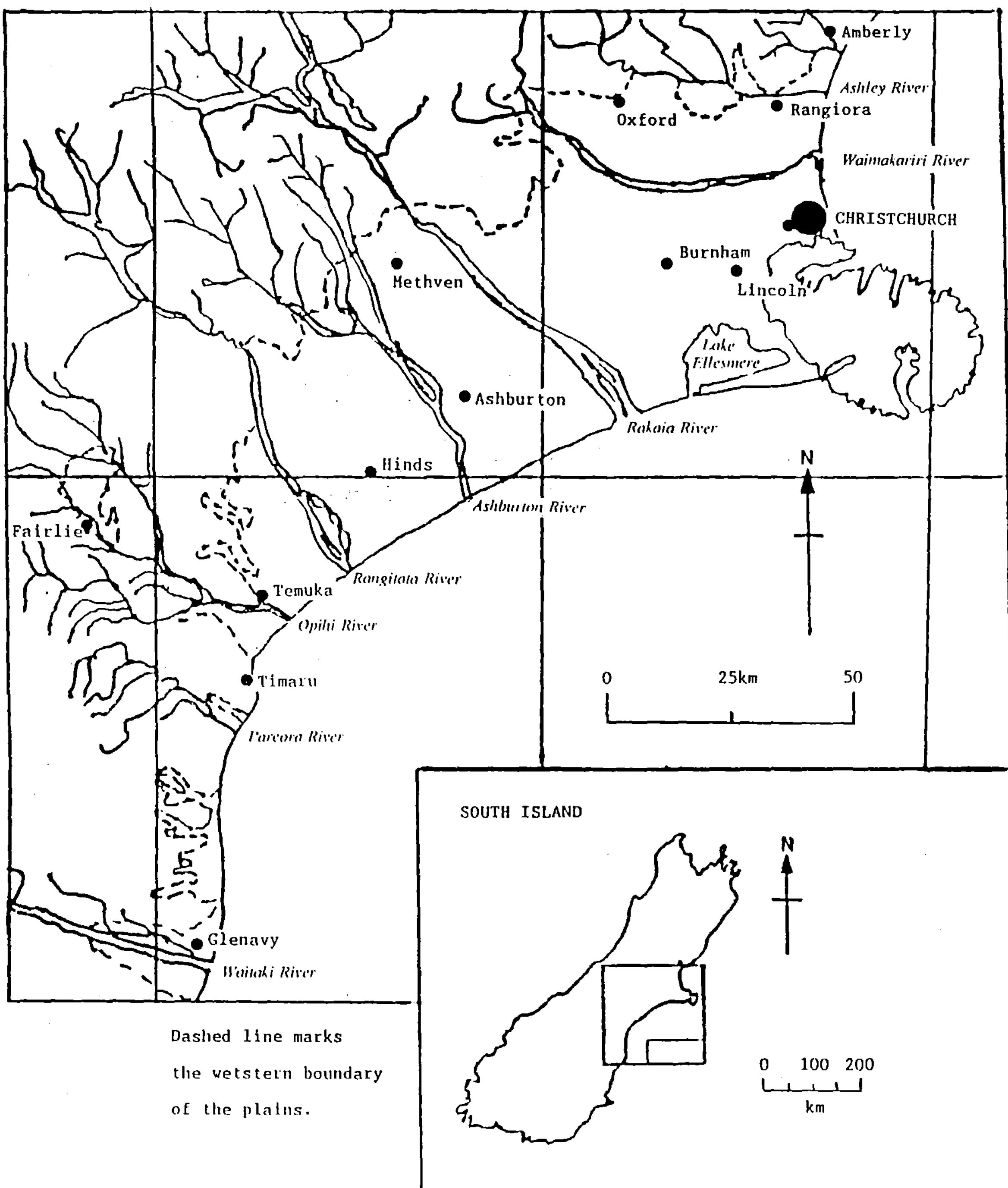
The climate is sub-humid and cool temperate. Rainfall is low (600-750 mm) but quite evenly distributed through the year. Summers are warm with occasional hot north westerly winds. Winters are cool with frequent frosts and occasional light snow (Coulter, 1975).

3.1.1 Temperature.

The mean annual air temperature at Lincoln is 10.8 ^{o}C (1931-1960) with a winter mean low of 4.8 ^{o}C in July and a mean high of 16.0 ^{o}C in January (Figure 3.2b). The average developmental time each year is 2440 degree days above 5 ^{o}C.

Each year there is a probability of 20 days with air temperatures above 27 ^{o}C. On average 38 or more days are expected to have minimum air temperatures below 0 ^{o}C. Ground frosts occur 90 days a year and may occur in any month, even near the coast.

Figure 3.1 Diagram of the Canterbury Plains region.



Dashed line marks the wetstern boundary of the plains.

The soil temperatures under pasture for an average year are shown in Figure 3.2c. At 10 cm depth the average annual temperature is 10.7 ^{o}C with a winter minimum average temperature of 3.9 ^{o}C in July and a summer maximum average of 17.3 ^{o}C.

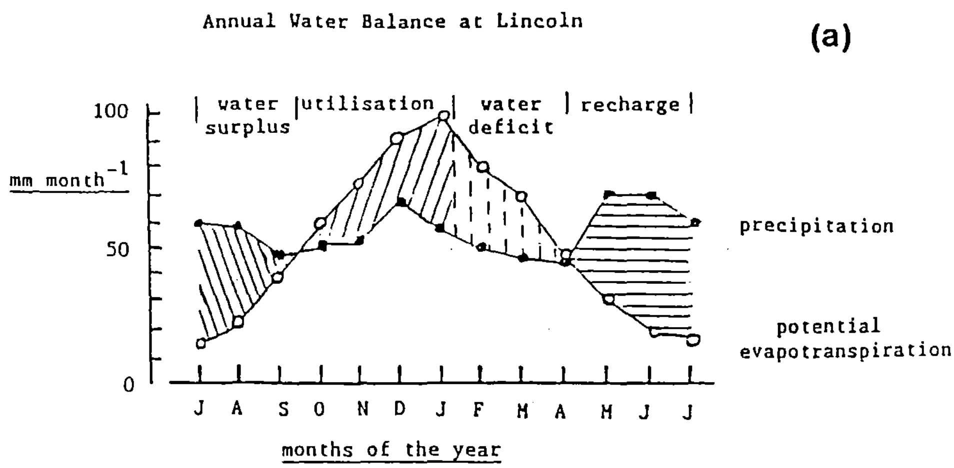
The temperature regime over most of the plains is similar to that at Lincoln College. A drop in temperature of less than 1 ^{o}C occurs south to Timaru, and a similar, very slight drop inland to Methven on an annual average basis.

3.1.2 Rainfall and evapotranspiration.

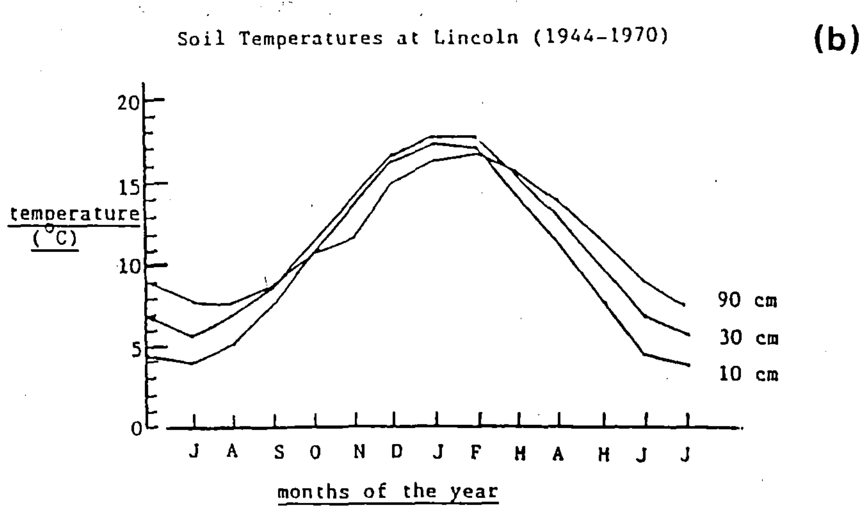
Lincoln receives an average of 670 mm of rain a year, varying between 400 and 800 mm. The variation inland from the coast corresponds with increasing altitude up to 1030 mm average at Methven (300 m a.s.l.) and 890 mm at Oxford (110 m a.s.l.). This increase in rainfall westwards means that smaller soil water deficits are experienced inland than at the coast. Potential evapotranspiration is 635 to 645 mm a^{-1} over most of the plains. The January average is 4 mm d^{-1} and the July average 0.3 mm d^{-1}.

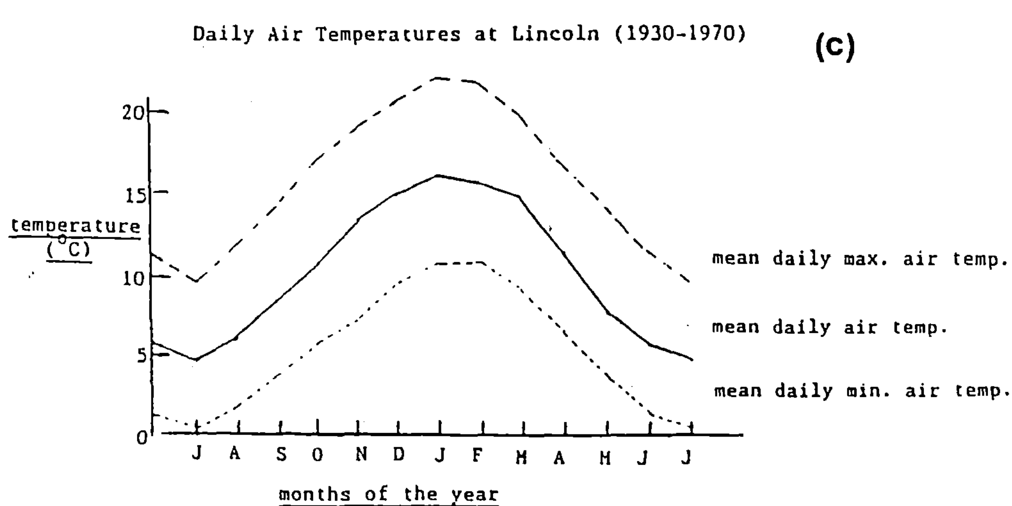
In an average year at Methven no days of soil water deficit will occur and 415 mm of water will have to be drained in the winter. On the other hand, the Thornthwaite diagram for Lincoln shown in Figure 3.2a predicts an average summer deficit of 100 mm in a soil with 102 mm of available water (such as a Templeton silt loam). Lincoln also expects a total of 100 days of drought. Despite this, an average of 200 mm will percolate down to the water table or run off the land, mainly in winter.

Figure 3.2 Thornthwaite water balance diagram (a), soil temperatures (b) and daily air temperatures (c) for Lincoln (long term means) from Cox (1978).



Total annual precipitation 660 mm
Total annual potential evapotranspiration 640 mm





The maximum daily precipitation that is likely to be exceeded once in 20 years is 100 mm d^{-1} on the plains. On this basis any soil that is capable of infiltrating water at 2 cm h^{-1} or faster is unlikely to give rise to run-off.

The availability of water is the most important factor in agricultural practice on plains soils. This is especially true in low moisture holding soils and in coastal locations.

3.1.3 Wind.

The prevailing winds of the plains are north easterly at the coast becoming north westerly inland towards the Southern Alps. This has been important for loess transportation in soil formation (see section 3.2.1). Coastal north easterlies are on-shore breezes rarely exceding a speed of 6 m s^{-1}. For 55 days a year south westerlies bring a colder air mass, and almost all the rain. Inland and to the South some summer convectional rain occurs. Twenty four days a year are considered 'calm', usually in the winter when anticyclones are associated with ground frost by night and warm days.

The north westerly is a Föhn wind which blows hot and dry in the summer. For 2-5 days a year winds of >35 ^{o}C, relative humidity <45 %, speed >20 m s^{-1} cause severe drying conditions. In such conditions unprotected soil may lose in excess of 7 mm d^{-1} of water and wind erosion readily occurs, especially in bare cultivated ground (Stringer, 1985). Plants may experience severe water stress under these conditions. It is not surprising that the north westerly winds are responsible for erosion when considering that this wind was originally responsible for the loessial deposits that make up so many of the plains topsoils.

3.2 CANTERBURY PLAINS PEDOLOGY.

Much of the information in this section is derived from Kear et al. (1967) and Cox (1978). These two reports cover the plains as a whole and part of Paparua County respectively. The plains soils are chiefly yellow-grey earth/recent soil intergrades (Gibbs, 1980), with recent soils near rivers and near the east coast in the Christchuch-Lincoln area and around Ashburton.

3.2.1 Geology

The Southern Alps of Canterbury at the heads of the major rivers are predominantly Greywacke rock. The substrata of the plains was formed by glacial outwash of gravels from the Alps in the early Quaternery period. The area is a succession of flood plains and fans of the major braided rivers: the Ashley, Waimakariri, Rakaia, Ashburton, Rangitata, Opihi and Waitaki (see Figure 3.1). Smaller rivers occupy depressions in the landscape. The slope of the plains decreases from west to east. At Lincoln the slope is about 0.3 %. Much of the plains is susceptible to flash flooding.

Subsequent to a series of Pleistocene glaciations, loess deposits were blown from the river beds from north west to south east. Deposits are thus sorted from coarse to fine in a south easterly direction from rivers. Most of the plains have loessial topsoils over alluvial deposits. The exceptions are low lying areas with sedimentary deposits and areas currently or recently being reshaped by rivers.

3.2.2 Biotic factors.

In the mid 19th Century, early European settlers found most of the plains under silver tussock (*Poa caespitosa*) and hard tussock (*Festuca novae-zelandiae*). Podocarp forest is thought to have dominated the area up until 1000 to 500 years ago. Since that time repeated fires and a possible change in climate have prevented reforestation by podocarp. Drier lands supported kanuka (*Leptospermum ericoides*) and matagouri (*Discaria toumatou*). In low lying and swampy areas flax (*Phormium tenax*) and raupo (*Typha orientalis*) were found.

The vegetative input to the formation of the plains soils has chiefly been governed by the water holding capacity of the loessial topsoils and alluvial subsoils. Often the groundwater level has also had an influence on vegetation. The question of water balance is still the most important single consideration in land use on the plains.

3.2.3 Soil associations studied.

The major association studied was the Templeton/Wakanui/Temuka association. These are low terrace or fan soils known as yellow-grey earth/recent soil intergrades. The differences between the series are chiefly by drainage class and age group (see Table 3.1). The association accounts for 140 000 ha (19 %) of the plains. Mostly, these soils are silt loam topsoils over alluvium of various nature. Sometimes drainage class is controlled by groundwater systems rather than soil texture.

Ages correspond with position in the landscape. Older associations such as the Lismore age group occupy the high river terraces, with the

Templeton age group on intermediate terraces and the Waimakariri age group on the low terraces. The recent soils are found on the existing flood plains.

Table 3.1 Soil associations, age and drainage class.

Soil age	Drainage sequence		
	Well drained	Mottled	Gleyed
Post-glacial			
Selwyn age group < 300 years.	Selwyn	Kaiapoi	Taitapu
Waimakiriri group 700 - 2 400 years.	Waimakiriri	Kaiapoi	Taitapu
Templeton group 3 000 - 10 000 years.	Templeton Eyre	Wakanui	Temuka
Otira Glaciation			
Lismore group >20 000 years.	Chertsey Lismore		

A small amount of time in this study was spent working with soils of the Waimakiriri/ Kaiapoi/Taitapu association. These soils are more recent than those of the Templeton association, and all may be found within 20 km of Lincoln College.

The sampling procedures used did not allow study of stoney soils. The stoney Lismore soils (180 000 ha), stoney phases of the Templeton series (26 000 ha) and the shallow Eyre Soils (44 000 ha) together account for 250 000 ha, or one third of the Canterbury plains soils.

One other soil that was studied was situated 10 km west of Rangiora on downs margin land. This land is rolling with Ashley series in depressions and Mairaki series on raised areas. Some sites on Mairaki soils were studied. This series has a poorly drained silt loam topsoil over a deep silt loam subsoil which is naturally compacted.

3.3 LOCAL LAND USE PRACTICES.

3.3.1 History.

This short account of relevant history of the plains is intended to aid the general understanding of the thesis. Much of the information was derived from Kear et al. (1967).

The plains were completely occupied by 1855, mostly by European and Australian immigrants. Merino sheep were brought from Australia and raised on much of the land. Wheat was grown for domestic consumption. The principal produce was fat lamb most of which was exported to Europe. This traditional market has declined since the formation of the European Economic Community (Dunbier, 1983). There has been a compensatory increase in the Middle Eastern, Asian and Pacific markets.

Kear et al. (1967) observed a trend towards increasing arable cropping in Canterbury. This would mean an increase in the cultivation of soils, especially those with comparatively high available water volumes such as the soils of the intermediate and low terraces which have been studied for this thesis.

Areas of cultivated land have suffered from water erosion. Kear et al. (1967) cited other work which showed that in Geraldine County in South Canterbury 44 % of soils were eroded, and 15 % were severely eroded through sheet and gully erosion. A recommendation was made that no cultivation should occur on slopes greater than 15°.

Erosion is nothing new to Canterbury. Stringer (1985) reported that there was a very severe windstorm in 1898 causing widespread soil erosion. Stringer predicted that under present land use such a storm would cause catastrophic damage to soils and plants. He found that the traditional cultivations of ploughing and working down a seed-bed are practiced on almost all farms where a new crop is being drilled. This practice leaves soil particularly prone to soil erosion, especially by north west winds. Osborne (1984) commented that unnecessary cultivation of soils in Australia might be linked to the old pioneer mind-set of "breaking the land".

3.3.2 Present trends.

At the time of writing, the farming community in New Zealand as a whole is going through a period of rapid adjustment. The trend perceived by Kear et al. (1967) towards increased arable cropping of land has been confused by a number of factors, chiefly the world glut in cereals caused by overproduction in the E.E.C. and the U.S.A.. The trend may be more obvious in future years (Engelbrecht, 1983).

The Canterbury United Council (New Zealand) Advisory Group (1983) projected that economic development of Canterbury will depend greatly on enhanced primary production of foodstuff and fibre. Greer (1983) gave projections of the effects of an intended irrigation scheme for 140,000 ha of land between the Waimakariri and Rakaia rivers (known as the "Central Plains Irrigation Scheme"). This would increase the cropped area from 36,000 to 73,000 ha. While there would be a decrease in the area of stocked land, the extra carrying capacity would increase the stock units for the area from 1.1 million to 1.3 million (Greer, 1983).

Such a scheme would greatly increase the intensity of arable cropping and probably of cultivations.

Engelbrecht (1983) gave one farmer's attitude which summed up the general reluctance of farmers to adopt direct-drilling. He said "There is a place for direct-drilling - someone else's place". It is possible that direct-drilling will not be widely adopted until arable farming becomes more intensive and timeliness of drilling becomes more important. Engelbrecht predicted that arable farming surely would become more intensive on the plains over the next 10 or 20 years.

These trends may mean that the research presented in this thesis is on the leading edge of the trends in agriculture. With carefully chosen extension work, the conclusions of Chapter Ten may help to prevent some of the mistakes that can be made in the management of topsoil structure with more intensive land use.

CHAPTER FOUR

FIELD TRIALS, SURVEY AND LABORATORY METHODS.

There were three main sources of field data; two field trials and a survey of selected sites within 50 km of Lincoln College. The design of the trials, the field measurement methods used at each location and the analytical procedures adopted are described in this chapter.

Experimental methods used for root and earthworm studies are not described here. Details of those methods appear in the relevant chapters. This chapter is soley concerned with soil physical analysis. Field measurement techniques and some field core laboratory methods are described and discussed.

4.1 TILLAGE AND CROPPING EXPERIMENT

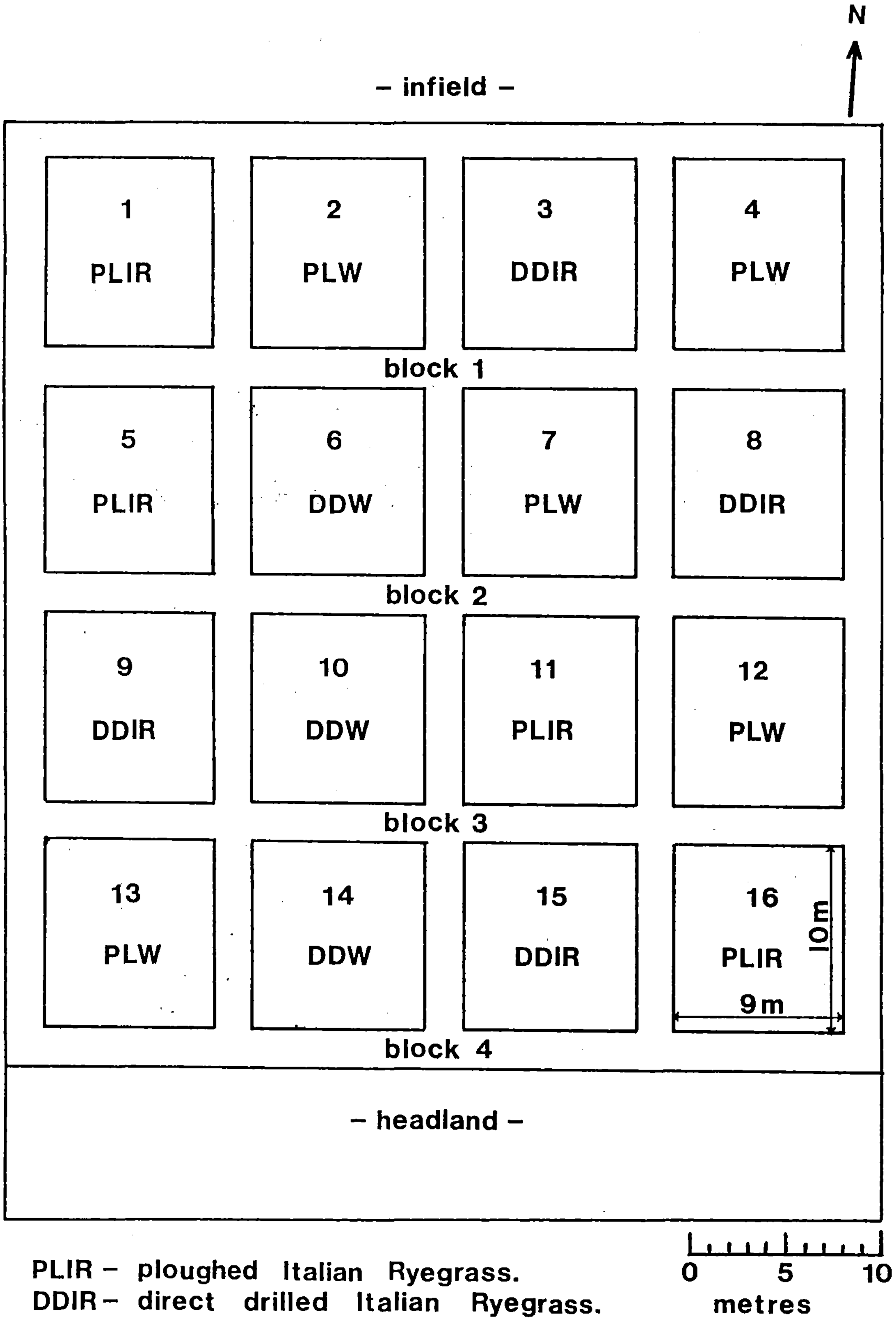
The aims of this experiment were (i) to compare the specific effects of wheat and Italian ryegrass on topsoil structure and (ii) to compare these crops under two seed-bed preparation treatments of ploughing and working against direct-drilling. The experiment lasted two seasons.

4.1.1 Design.

A randomised, blocked design was used. Blocks were arranged from infield to headland as shown in Figure 4.1. There were four replicates of each treatment combination.

The wheat used was *Triticum aestivum* L., cv. Rongotea, which will hereafter be referred to simply as 'wheat'. The production of this variety tends to account for 50 % of the national wheat yield from year to year, and it is the most popular variety in Canterbury (Wilson, 1985). The Italian ryegrass used was *Lolium multiflorum* L., cv. Grasslands "Tama", hereafter simply referred to as 'Italian ryegrass'. This particular variety, as distinct from some other varieties, is strictly an annual plant (Langer, 1973). It was chosen so that grass could be compared with wheat on an annual basis.

Figure 4.1 Design and treatments of the tillage and cropping experiment.



PLIR – ploughed Italian Ryegrass.
DDIR – direct drilled Italian Ryegrass.
PLW – ploughed Wheat.
DDW – direct drilled Wheat.

4.1.2 Management.

Some studies have examined the differences in soil structure under a succession of wheat crops compared with a constant grass crop (Low, 1972). In that study, Low's major conclusions were related to the effects of continuous cultivation rather than the wheat crop itself. In this experiment both crops were annual and both treated identically, even to the point of harvest date. Unfortunately, some aspects of identical management compounded irregularities in crop performance rather than simplifying them. Some examples of this are described in section 5.1.2. A complete diary of events is given in Appendix One.

4.1.3 Site.

The field site was located in paddock R17 of the Lincoln College Research Farm. The New Zealand grid reference is S83 832 423. The topography was flat with a negligible slope to the south east. There was no shelter within 100 m. This site was 20 m above sea level.

The soil was a Wakanui silt loam, a yellow-grey earth/recent intergrade in the N.Z. classification system (Kear et al., 1967) or a Dystric Eutrochrept by the USDA system (USDA, 1985). The profile was imperfectly drained with mottling and iron oxide concretions at all depths to 1 m.

The Ap horizon extended to 20 - 30 cm. Peds had a nut structure and organic matter varied between 4 and 8 %. The B horizon started at 20 to 30 cm and extended to between 40 - 80 cm. It was texturally similar to the Ap horizon with occasional clay loam and fine sand lenses. There was mottling with some iron nodules in a generally massive structure.

Usually there was a C_2 horizon of a more sandy texture below the B horizon at this site. This began at 40 to 80 cm depth and continued to depths greater than 100 cm. Different textural lenses existed in this C_2 horizon.

The site contained areas of soil that resembled the Templeton and Temuka series as well as the Wakanui series of the same association (see Section 3.2.3). Some examples of textural variability are given in Appendix Four. This variabilty may have had a considerable effect on infiltration rate measurements (Karageorgis, 1980) and the variability over short distances has been documented by Karageorgis et al., (1984).

The previous history of this site was continuous wheat cropping for six years. It was assumed that such a history would have resulted in a poor structure. However, during this period cultivations had been kept to a minimum and organic matter inputs from weed infestation was appreciable as is reported in Chapter Five. This may have partially off-set the decline in structure that might have been expected. Even so, this site was in a relatively poor structural condition compared with other sites studied (see Chapter Nine).

An important feature of the site was that it was previously part of a "take-all" trial. The site used had not been fertilised or limed for at least two years and had been a relatively low yielding treatment in the take-all trial (Close, 1986). The agronomic limitations of the site are discussed in Chapter Five.

4.1.4 Sampling procedure.

In the first season of this experiment the sampling procedure for soil physical measurements was not entirely standardised due to inexperience and lack of reliable equipment. By the end of the first season the sampling procedure was standardised. This standardised procedure was also used for the pasture species trial site (Section 4.2.4) and for survey sites (Section 4.3.1). The procedure was as follows;

Day 1 Harvest of shoot material from a 1 m^2 quadrat (when necessary)

Measurement of infiltration rate at steady state.

Day 2 or 3 Measurement of penetrometer resistance to 50 cm (and soil water tension at 15 cm).

Intact soil cores taken at 0-2 cm

" " " " at 5-15 cm depth.

Loose samples taken at 0-2 cm and at 5-15 cm.

A profile pit was dug where appropriate.

Day 5 Earthworms were collected and counted, as appropriate.

The field measurement techniques that were used are described below.

4.1.4.1 Infiltration Rate.

Infiltration rate was measured using a double ring apparatus. The inside ring, from which measurement were taken, was 30 cm in diameter.

The outer guard ring was 50 cm in diameter. This double ring system was used by authors such as Astapov and Dolgov (1959) and Bertrand (1965). A constant head of water was maintained using a mariotte device. The rings were made from 3 mm steel plate. Sites were usually gently wetted before driving the rings into the soil surface in order to minimise shattering of the soil surface. A rigid driving head was used when positioning the rings to ensure level penetration of the soil surface to 2 or 3 cm depth.

One measurement was made for each plot, so there were four replicates per treatment. For each measurement, three steady readings were usually determined within 3 hours of initial ponding. The soil surface temperature was measured when a steady rate of infiltration had been achieved. Using that temperature, the measured infiltration rate was ajusted using a factor from the table of water viscosities (page F38 of Weast, 1984) to compensate for variation in temperature to a standard of 20 ^{o}C so that winter and summer measurements could be compared.

4.1.4.2 Penetrometer Resistance.

An Eijkelkamp analogue cone penetrometer was used with a 1 cm^2 60^{o} relief cone. This instrument was pushed vertically downwards at a speed of 2 cm s^{-1}. Readings were taken at 10 cm increments to 50 cm depth.

Penetrometer measurements were made in the position of the outer infiltration ring area one or two days after infiltration depending on drainage conditions. Soil water potential was checked to be between -0.1 and -0.2 bar using a 'Soilmoisture Equipment Corp. "Quick Draw" Soilmoisture Probe', which measures soil water tension between zero and 1 bar.

The mean for each treatment at each depth was determined from sixteen replicates. These were grouped into four lots of four replicates, where a group of four were taken from each of the areas where infiltration rate had been measured.

One disadvantage with this method was that only the maximum resistance for each depth increment was measured. Values were therefore not means, as such, but means of maximums. Nevertheless, useful empirical comparisons can be made with the data.

4.1.4.3 Intact Soil Cores.

Cores were taken at 0-2 cm with a diameter of 7.65 cm, a height of 2.2 cm and a volume of 101.6 cm^3. The wall thickness of the core containers was 0.35 cm. These cores were trimmed in the field and supported below by a muslin sheet secured by an elastic band to the core container.

Cores were taken at 5-15 cm depth with a diameter of 10.3 cm, a height of 10.0 cm and a volume of 833 cm^3. The wall thickness was 0.35 cm. These too were trimmed in the field, but were supported by fly-net sheets so that saturated hydraulic conductivity tests could be performed. Both the small and large core containers were made from PVC piping with a lower cutting edge tapered to a wall thickness of 0.1 cm.

Cores were taken on the 2nd or 3rd day after infiltration rate measurements depending on drainage conditions. Containers were driven into the soil using a driving head and a 3 lb hammer. Care was taken to relieve the pressure around the core container at frequent intervals.

Note that cores were always taken at similar soil water tensions. This was to to avoid errors due to varying soil strengths at different water contents at the time of sampling. This subject has been addressed separately as a draft paper (Lance and Gibbs, unpublished), which has been included with this thesis.

4.1.5 Analysis.

The design was chosen to facilitate rapid analysis of results using a GENSTAT anova. Each complete set of data (16 datum points) was analysed for differences between botanical treatments, cultivation treatments and for botanical/cultivation interactions. The variance accounted for by blocks was removed using a block command.

Throughout this thesis a least significance level is $p<0.05$ unless otherwise stated. Each set of data was checked for normal distribution. Where appropriate data transformation was used to normalise data distribution. Where data transformation has been used in this thesis it is stated.

4.2 PASTURE SPECIES EXPERIMENT.

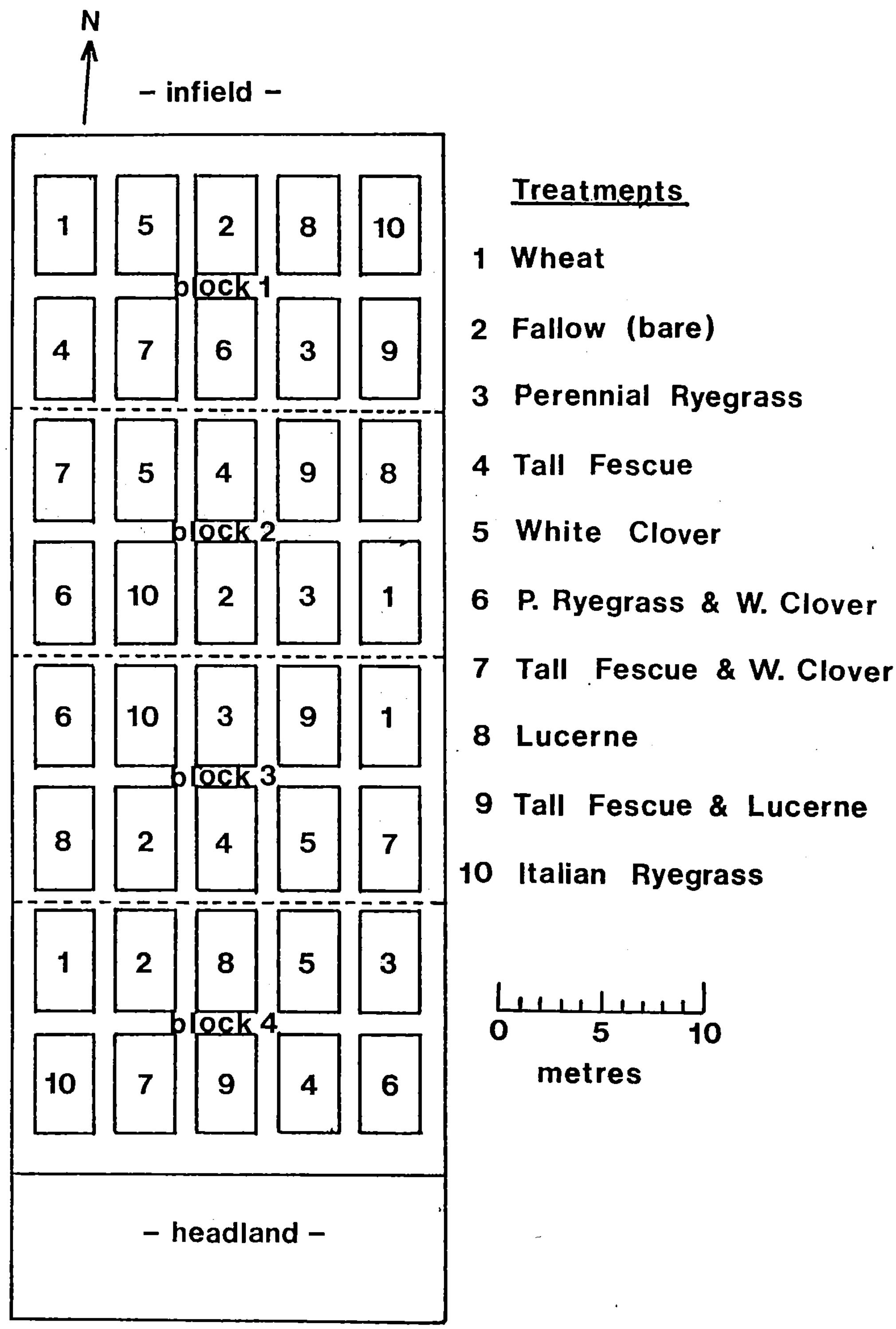
A selection of pasture species, including those in the tillage and cropping experiment, were sown into a ploughed seed-bed and allowed to grow for two seasons continuously. The aim of this experiment was to compare the effects on soil structure of a range of pasture species under moderate fertility conditions. Some species combinations were used. A complete list of species treatments appears in Figure 4.2.

4.2.1 Design.

A randomised, blocked design was used. Blocks were arranged from infield to headland as for the Tillage and Cropping Experiment. This design appears in Figure 4.2. Each treatment was replicated four times.

The wheat and the Italian ryegrass used were the same as for the tillage and cropping experiment. The perennial ryegrass used was *Lolium perenne* L., cv. Grasslands "Nui"; tall fescue was *Festuca arundinacea* L., cv. Grasslands "Roa"; white clover was *Trifolium repens* L., cv. Grasslands "Huia" and the lucerne used was *Medicago sativa* L., cv. Grasslands "Rere". Only the wheat and Italian ryegrass were annuals.

Figure 4.2 Design and treatments of the pasture species experiment.



Plot size 3 x 5m

4.2.2 Management.

After the initial drilling of the crops the only soil disturbance was the redrilling of wheat and Italian ryegrass for the second season using a direct-drill. No grazing or cutting occurred between sowing and harvest. At harvest all the plots were mown to within 2 cm of the soil surface and the foliage was removed. A complete diary of events is given in Appendix Two.

It should be noted here that no nitrogen was used on this area for the two years prior to the experiment or during the experiment. This was intended to show how the species used performed under the moderate fertility conditions prevailing according to MAFF (UK) as reviewed by Cooke (1975).

4.2.3 Site.

The trial site was 21 metres East of the Tillage and Cropping Experiment. The history and soil type are the same as for that experiment (see 4.1.3).

4.2.4 Sampling procedure.

Sampling was carried out on two occasions, and that was at harvest at the end of each season (see Appendix Two). The techniques used were the same as for the tillage and cropping experiment.

4.2.5 Analysis.

This design was suited to rapid analysis using a GENSTAT anova. The anova was adjusted to ignore data from the two treatments (8 and 9) sown to lucerne which failed to establish.

The variance accounted for by blocks was removed using a block command. The species treatment means were tested for significant differences individually. There were no other treatments or interactions that could be tested. The level of significance was $p<0.01$ to compensate for chance differences that might have occurred due to the large number of treatments.

While decreasing the probability level makes the chance of incorrectly rejecting the null hypothesis less likely, the chance of retaining the null hypothesis incorrectly is increased (Carmer, 1976). Carmer debated the point that when comparing a number of crop contrasting treatments in a trial, with many more degrees of freedom than one, there may be a case for increasing the probability level as high as 20 or 40 % in order to be more sure of not retaining the null hypothesis incorrectly.

This line of reasoning was not used in setting probability levels for this thesis. Where any doubt over comparability existed, or where the chance of accidental significance was enhanced by a large number of contrasted means (or a large number of compared correlations), then a lower probability level was used. This decreased the chance of rejecting the null hypothesis incorrectly. In short, the levels of significance were selected to err on the side of over-rigorous testing for significance.

4.3 THE LOCAL SILT LOAM SURVEY.

The original aim of the local silt loam survey was to measure physical properties of topsoils with well documented histories. This was undertaken to put the results of the two field trials in perspective. The survey was expanded so that sites with traffic compaction, treading damage and a range of different crop types were also sampled. Particular reference was given to sites with a range of earthworm population sizes with different management histories.

4.3.1 Design.

Sites selected were confined to the silt loam or heavy silt (silty clay) loam texture classes. This is shown in Figure 8.1. Otherwise sites were selected to study the following features;

(i) the effect of native vegetation,

(ii) contrasting management practices,

(iii) characteristics of different crop choice

(iv) the effect of traffic

(v) the effect of cattle treading.

Specific details of each site appear in Appendix Three, including location, management history, soil profile description and complete physical data measurements. All the sites visited were within 50 km of Lincoln College. All sites were on the near level flood plain of the Waimakariri river except a group of five sites on the Mairaki Downs west of Rangiora (sites 7-11).

4.3.2 Analysis.

The sampling procedure was the same as was described in Section 4.1.4. Measurements were made from September to May each year. Since all sites were autumn sown, direct-drilled or undisturbed, this meant that sampling was effectively made from the middle to the end of the cropping season. The effects of any cultivations had had the winter to settle and crops were either well established or harvested.

Some groups of sites were analysed separately where appropriate. For example, sites 1-6 were a field experiment. Other field experiments were sites 12-19, and sites 27-34 (two seasons of the pasture species experiment), sites 37 & 38 (a DSIR treading trial) and sites 40-43 (the second season of the tillage and cropping experiment). Results of these groups appear later in the thesis where appropriate.

Two other groups of sites were analysed together. Sites 7-11 on the Mairaki downs were chosen to contrast crop histories under similar tillage management on the same soil type. Another group was made up of sites 25, 26, 35 & 36. This was a case history study where site 26 was the reference area and site 25, 35, & 36 were chronological treatments of an area suffering from traffic compaction. The results of this case study appear in Section 9.2.

As well as comparison within groups, the entire data-set was analysed for correlations between physical measurements. Where appropriate, two factor and/or stepwise multiple regression analysis were also performed using the MINITAB computer package. The results of this analysis appear in Section 8.2. It is important to note that it was

NOT the intention of the survey to select representative sites that would characterise the silt loams of the Canterbury plains. The intention was more directed to examining the features previously listed in Section 4.3.1.

4.4 LABORATORY TESTS ON FIELD SAMPLES.

Measurements of infiltration rate and penetrometer resistance were made in the field. Saturated hydraulic conductivity, earthworm burrow numbers, total and ε_{100} porosities, particle density, aggregate stability and organic matter content were all determined on field samples brought in to the laboratory. The methods employed for these laboratory measurements are discussed in this section.

4.4.1 Saturated hydraulic conductivity.

Saturated hydraulic conductivity (K_{sat}) measurements were made on the 5-15 cm intact cores using an apparatus similar to that described by Klute (1965). Cores were stood overnight on a saturation tray prior to measurement. There was no such event as steady state conductivity, so measurements were made at 40 and 60 minutes after first imposing the hydraulic potential of 5 cm (0.005 bars). The results of this test are of minor importance to this thesis. Great variability was observed and data usually had to be square root transformed to achieve a normal distribution for analysis of variance. Consequently, linear standard errors could not be calculated.

4.4.2 Earthworm burrow numbers.

Earthworm burrow numbers were counted at 10 cm depth in the 5-15 cm depth cores used for K_{sat} in the laboratory. Burrows with a diameter greater than 1 mm with obviously regular shape and evidence of a mucus lining to their walls were counted as earthworm burrows.

4.4.3 Total and ε_{100} porosities.

Total porosity (ε_t) was calculated from dry bulk density (ρ_b) and particle density (ρ_p) according to equation 4.1 and expressed as a percentage.

$$\varepsilon_t = (1 - \frac{\rho_b}{\rho_p}) \times 100 \qquad (4.1)$$

The values of ε_{100} porosity were calculated from total porosity and the weight of water retained by the soil core on a tension table at -0.03 bars. This method has been documented by Stackman et al. (1972) and by Avery & Bascomb (1974). The relative percentage volume of water retained at 0.03 bars tension ($\theta_{0.03}$) was subtracted from total porosity to give ε_{100} porosity assuming a density of water of 1 g cm^{-3} at 20 ^oC as shown in equation 4.2.

$$\varepsilon_{100} = \varepsilon_t - \theta_{0.03} \qquad (4.2)$$

Cores were saturated and then allowed to equilibrate for one week at 0.03 bars of tension. This length of time was found by experimentation to be an adequate period of time for the drainage of the 10 cm high cores from 5-15 cm depth.

4.4.4 Particle density.

Particle density was determined for field trial sites and for survey sites at both 0-2 cm and 5-15 cm depths. This was achieved by water displacement under a vacuum according to the method of Boekel (1961). The method used oven dry soil in volumetric flasks and the volume occupied by evacuated submerged soil was determined by difference at 20 ^{o}C.

4.4.5 Aggregate stability.

A selected size range of air dry aggregates of 2-4 mm was prepared from the loose field samples. Every attention was paid to minimising disturbance. Natural clods from the field were broken at a friable moisture content and gently passed through a 4 mm sieve and then air dried. Once dried, aggregates not passing through a 2 mm sieve were used for aggregate stability determination.

Between 50 and 100 g of air dry soil were placed on a sieve and allowed to stand under water for 5 minutes. The sample was then raised and lowered for 5 minutes at a rate of 24 cycles per minute through a height of 2.5 cm, under water at all times.

Stability was simply calculated as a percentage of oven dry stone-free soil retained on the 2 mm sieve divided by the oven dry stone-free soil of the initial sample. This method was chosen after many other methods had been tested, the deciding factor being its simplicity. It was similar to the method used by Low (1954).

4.4.6 Organic matter analysis.

A major difficulty was observed with the traditional Walkley-Black method (Walkley & Black, 1934). Roots and organic matter were observed floating or suspended in the oxidation solution following wet oxidation. Since the root and macro-organic matter masses were of great importance to this study, a more complete method was required.

The method of Ball (1964) was adopted. This method involved loss on ignition at 375 ^{o}C. Ball found that at this temperature crystal lattice water loss was an unimportant error. This was verified by experimentation. It was also determined that no errors occurred in the presence of calcium carbonate. Root and macro-organic matter was totally ignited after 20 hours at this temperature, leaving only ash that was not ignited at 550 ^{o}C.

This method was therefore assumed to give a good estimate of organic matter. It was also very simple and large samples (10-20 g) could be used to decrease representative sampling errors. Soil was ground and reduced to particles less than 0.25 mm diameter for this determination. Results were expressed as a percentage of oven dry weight of soil.

CHAPTER FIVE

ROOT INPUTS AND ORGANIC MATTER STATUS UNDER VARIOUS CROPPING SYSTEMS.

Chapter Five

This chapter is concerned with the quantity and distribution of topsoil organic matter under different management systems and with inputs of root material from different crop species. In the first sections of the chapter specific differences in organic matter inputs to soil, especially from roots, of different crops is examined. The literature on this subject is reviewed and results from the pasture species experiment and the tillage and cropping experiment are presented. This part of the study pertains to pathways 8 and 10, combined, of Figure 2.1.

The second part of the chapter covers other management effects on soil organic matter content. In particular, the effect of cultivation on organic matter quantity and distribution is discussed. Literature on this subject is reviewed, and results from the tillage and cropping experiment are reported. Additional results from another controlled experiment and some silt loam survey sites are included. This study pertains to pathway 13, and to some extent pathway 5, of Figure 2.1.

5.1 CROP EFFECTS ON SOIL ORGANIC MATTER.

There has been some difficulty in correctly identifying cause and effect when measuring changes in organic matter content. Low (1972) made an extensive study of the effects of long term arable cropping and long term pasture. He observed a decline in organic matter with increasing years since pasture when growing arable crops. He concluded that the main factor causing this decline was repeated cultivation. The questions that have to be asked, however, are whether long term cultivations were responsible for the decline, or was it the fact that annuals were grown, or was wheat a particularly low yielder of organic matter, or was the management of above-ground organic matter responsible for this decline?

This review has been split into areas of management such that the crop effect itself is isolated from cultivation effects and from other effects such as residue management and the presence of growing crops. Attention has been concentrated on root inputs and the associated soil organic matter status under different crops.

5.1.1 Review of crop effects on organic matter inputs.

This section addresses the root production differences between crop species isolated from other management effects. Fogel (1985) estimated that 60-70 % of the below ground primary production entering the soil energy system is derived from roots. The substrate on which soil organisms work to create habitats for themselves is thus largely dependent upon root inputs (Jacks, 1963). This will be referred to again in Chapter Six in relation to earthworm populations.

In 1971, Batey & Davies reviewed the subject of soil structure for arable cropping. They included a table (Table 5.1) which showed reported weights of residues returned to the soil from different crops. This has been reproduced below;

Table 5.1 Organic residue returns from different crops from Batey & Davies (1971).

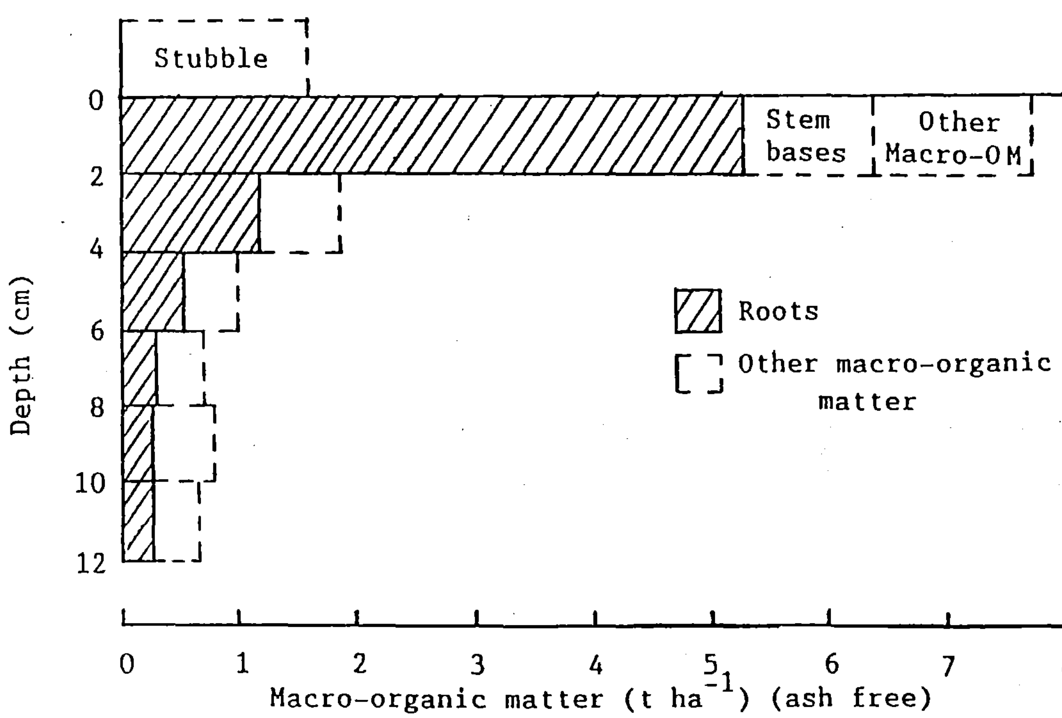
Crop/management	Organic residues ($t\ ha^{-1}$)
Grass	4.2
Cereal stubble	2.0
Cereal stubble + undersown grass	3.9
Winter wheat	2.5
Spring cereals	2.0
Beet, Peas, Beans	0.5
Farmyard manure @ 22 $t\ ha^{-1}$	4.25

It is important to note that growing root crops and legumes returned very little organic matter to the soil. Potatoes (not shown) tend to return similarly small amounts of organic matter (Strutt, 1970). It may also be seen from Table 5.1 that grass returned more organic matter than wheat or cereals, or cereal components.

No one species can be expected to be superior in all places at all times (Andrew, 1965). This is because the yield of different species, or even varieties, would vary with season and environment. On balance, perennial species give more constant organic matter inputs than annuals. Cheshire (1979) also concluded that the more consistent inputs from perennials was an important factor in organic matter levels compared with annual crops.

The rooting profiles of different species may have a differential effect on where in the profile new organic matter is produced. Weaver (1947) concluded that the positioning of organic matter by the growth of roots in the profile was an ideal way of maintaining and improving soil structure. Figure 5.1 shows a topsoil profile for macro-organic matter (retained on a 0.25 mm sieve) under a three year ley of perennial ryegrass/white clover from Garwood et al. (1972). Of the 9.3 t ha^{-1} of macro-organic matter in the top 12 cm, 57 % was from roots, 20 % from stems and stubble and 23 % other material. In the work of Pavlychenko (1942), roots were 70-90 % of the recorded input to soil. Crowns were thus 10-30 % of the yield. The relative contribution of roots and crowns to dry matter produced in the soil depends on herbage management.

Figure 5.1 Macro-organic matter profile under a three year ley from Garwood et al. (1972).



Clement & Williams (1964) experimented with many different grass and clover species in a soil with a history of annual tillage. They found no consistent species difference in the rate of organic carbon accumulation under leys in the top 15 cm of soil. Only in a highly replicated experiment was there a detectable species effect between a perennial ryegrass (Lolium perrene)/white clover (Trifolium repens) and a cocksfoot (Dactylis glomerata)/white clover ley after three years. This difference was detected when the standard errors of the means of organic carbon had been reduced to $\pm$ 0.009 percentage points. In this case the ryegrass ley produced an increase of 0.21 percentage points compared with 0.16 percentage points for the cocksfoot ley in the top 15 cm of soil.

In Britain, Troughton (1961a) found that very little difference in root weights occurred in the top 22.5 cm of soil between the grass species he used. Perennial ryegrass, cocksfoot, meadow fescue (Festuca pratensis) and timothy (Phleum pratense) all gave similar yields of roots. However, the same year (1961b), Troughton stated that a different four grasses (perennial ryegrass, cocksfoot, browntop (Agrostis tenuis), and chewings fescue (Festuca rubra)) had a far greater effect on root weight yield than four different grazing management treatments. In the latter study unusually high root weights were reported. Perennial ryegrass was supposed to have given the highest yield at 19.9 t ha^{-1} and the lowest was cocksfoot at 16.8 t ha^{-1} which were significantly different.

The high values of Troughton (1961b) may have occurred because of the methods employed which were described in Troughton (1951). Firstly the weights were not ash-free weights, and so a quantity of soil was likely to have been included. Secondly, root samples were only air-dried and not oven dried. Thirdly there was no mention of sorting out non root material. Consequently, it may be assumed that the 0-7.5 cm depth values included other macro-organic matter apart from roots.

Troughton (1951) showed profiles with unusually high concentrations of "roots" in the top 7.5 cm. His results suggested that about 80 % of the "roots" were found in the top 7.5 cm which, even under pasture, is an incredibly large proportion of the total root weight. It may have been more accurate if Troughton had termed the organic matter that he recovered from his 0.25 mm sieves as "macro-organic matter". The values of Troughton (1961b) are probably substantial overestimates of root weight.

Pavlychenko (1942) showed that the length of time that a broken sod was resistant to wind erosion was related to root strength and the length of time that roots persisted ~~which~~ varied between the grass species studied. He also showed that a combination of low root mass and low tensile strength of roots resulted in wheat having the lowest soil binding equivalent of any of the species tested. Pavlychenko found that wheat roots tended to be decomposed more quickly than roots of grasses which further reduced the value of wheat for preventing wind erosion.

Cheshire (1979) showed that the quality of organic matter is an important factor in the rate of decay and the usefulness of the material for soil structure. High tannin or lignin levels have been shown to inhibit decomposition. An extreme example of this would be mor soil litter layers which have high resistance to decomposition due to their high tannin concentrations. It would be expected that decomposition rate might also vary between pasture species, or even between varieties. In 1947, Weaver found that old perennial grass roots and rhizomes decayed more slowly than young perennial roots, and those more slowly than annual grass roots.

Working with a large number of legume/grass mixtures, Najmr (1957) found that lucerne (Medicago sativa)/grass mixtures contributed the largest amounts of macro-organic matter to the top 60 cm of the soil profile at 9.8 t ha^{-1} of roots, stubble and crowns. Red clover (Trifolium pratense)/grass mixtures yielded 9.4 t ha^{-1}, and other legume/grass mixtures were studied. The most useful companion grasses to lucerne and red clover were tall fescue and harvest oats (Avena sativa). Najmr observed that 70-80 % of this macro-organic matter was fine roots, supposedly a more readily decomposable fraction. The work was conducted on an arable soil over two years with unusually dry weather.

In Canterbury, Watkin (1975) found that lucerne, tall fescue, prairie grass (Bromus willdenowii) and Yorkshire fog (Holcus lanatus) gave the greatest herbage yields of a wide range of pasture species. The Canterbury conditions tended to favour deep rooting pasture species, especially in late summer and autumn. The problem of Argentine stem weevil (Listronotus bonariensis) attacking perennial ryegrass aggravated the differences in autumn.

The work of Gibbs (1986), in Canterbury, showed that when perennial ryegrass was grown on an annual arable basis alongside wheat (being killed off and resown annually), wheat produced more roots (1.6 and 1.4 t ha^{-1}) than perennial ryegrass (0.8 and 0.7 t ha^{-1}) over two years. Gibbs therefore concluded that there was no intrinsic ability of perennial ryegrass to produce more roots than wheat on an annual basis.

Also in New Zealand, Robinson & Jacques (1958) found that grasses were better than clovers at stabilising aggregates. This was assumed to be because the grass root systems were more greatly ramified than the clovers. They also found that aggregate stability was correlated with root weight and the rate of root decomposition to form microbial biproducts. Robinson & Jacques found that chewings fescue (Festuca rubra cv. "Fallax") in particular, and to some extent cocksfoot, produced a fine granular soil structure whereas perennial ryegrass produced a coarse structure.

In order to minimise the effect of cultivation in an annual versus perennial contrast, the annual species must be re-established each year with minimal disturbance, such as direct drilling. This was attempted for the work reported in this thesis in the pasture species experiment.

5.1.2 Pasture species experiment agronomy.

The aim of the experiment was to identify any differences in root production between the species used and to identify crop effects on soil structure. The format for this experiment was described in section 4.2. It should be noted that management was principally that of an arable system. Foliage was harvested once a year. Perennial species were allowed to regrow and annuals were resown. The major management input was frequent herbicide applications to achieve pure swards. A diary of events and management details is given in Appendix Two. Rainfall and potential evapotranspiration figures for the period of the study are given in Appendix Five.

Rainfall in both years of the experiment was less than average with 592 mm in 1984 and 483 mm in 1985 compared with the long term mean of 680 mm. The distribution of rain was uneven (as shown in Appendix Five) such that 61 % of the 1984 rainfall fell from October to December and

35 % in 1985 fell in November and December. There was very little rainfall during the establishment phases (autumn) of the experiment in both years.

This pattern of rainfall also made controlling weed growth in the spring very difficult. It allowed fungal diseases in wheat to rapidly establish when weather conditions were unfavourable for control measures (particularly in 1985) and caused some lodging of wheat and grasses. The small amount of rainfall during establishment meant that the soil surface experienced less destructive force than might have been expected. No irrigation was used.

Foliar yields were measured once a year at the end of December. Foliage was cut from 1 m^2 quadrats as near to the soil surface as possible and dried at 70 ^oC. The results obtained are shown in Table 5.2. In the second season, 26 % of the dry matter of the wheat plots was weeds. The figure used for statistical analysis was the total. All of the bare fallow yield was weeds and a large proportion of the first season's white clover yield was also weeds. The second season of white clover appeared to be a very pure sward.

The grain harvests are not given. Wheat was badly damaged by birds and only a small proportion of the harvest index was recovered. This probably occurred because of the early ripening of the wheat in this study relative to surrounding crops. This problem also afflicted Evans (1976). However, the centre of this study was the root system which appears to have performed normally, (see Section 5.1.4).

Table 5.2 Foliar dry matter yields for two seasons of the pasture species experiment.

Crop treatment	26/12/84 ($t\ ha^{-1}$)	28/12/85 ($t\ ha^{-1}$)
Wheat	8.4 a	7.8 ab (5.8)
Fallow	1.2 d	0.3 c
Perennial ryegrass	8.2 a	7.2 ab
Tall fescue	6.2 bc	9.4 a
White clover	5.0 c	5.4 b
Per. ryegrass/W. clover	8.1 ab	6.4 b
Tall fescue/W.clover	5.6 c	7.3 ab
Italian ryegrass	6.8 abc	6.8 b
L.S.D. ($p<0.01$) =	2.0	2.5

Means NOT sharing letters within vertical data-sets were significantly different ($p<0.01$).

During the first year, perennial ryegrass, Italian ryegrass and wheat gave the highest yields. By the second season tall fescue was yielding highest at 9.4 t ha^{-1} dry matter. Clover in grass/clover swards was negligible. Grass/clover swards may therefore be regarded as grass only, but at lower sowing rates than the intentionally pure grass swards. For root analysis, it has been shown that grass/clover swards were indistinguishable from pure grass swards. Consequently, no root data for grass/clover swards will be presented.

Fraser (1986) considered that April was rather late for sowing tall fescue which is more temperature sensitive than the ryegrasses or wheat. Tall fescue might have shown its higher yielding capacity in the first year if the sowing date had been earlier. The sowing date used (first week of April) was appropriate for the other grasses and clover, but a little earlier than usual for wheat. There was no clear overall difference in yields between the years.

5.1.3 Method of root yield assessment.

Root cores were taken at anthesis in the second season of this experiment. Work by Gregory et al. (1978) showed that the maximum root weight for wheat occurred at anthesis and then declined. Choosing the time for maximum root weight was thus related to a plant developmental stage and not to calendar time or time since sowing. For grasses, Garwood (1967) showed that peak root weight also occurred at or around anthesis, as long as no unusually heavy falls of rain occurred in the late spring or summer. Anthesis was used as the time for sampling roots for this thesis.

It has been estimated by Goss & Reid (1981) that undetected organic matter production (through die-back of roots, sloughing off of cells from root tips, exudation and leakage) may amount to 40 % of the dry root weight, or 20 % of plant dry matter. Gibbs (1986) estimated that unseen production might be as high as 60 % of the dry root weight at anthesis and Lynch & Panting (1980) also used a value of 60 % for their calculations. It is important to remember that root weights at anthesis, while a maximum value for the season, do underestimate total production for the year of below ground organic matter. The process of production and decompositon of dry matter is continuous.

Four cores per treatment were taken, one from each of the replicate plots of a treatment. Cores were taken from between rows, not at random. Results are probably conservative estimates of root weight, but they probably more accurately reflect the general field condition than samples from beneath rows. Besides this, with only four replicates per treatment, sampling on rows might have caused positive skewness in the data-set.

Cores were taken to a depth of 1 m using a power auger which gave intact cores of 5.1 cm diameter. These cores were broken at 5, 15, 25, 35, 50, 65, 80 and 100 cm depth. The two faces at each break were carefully excavated to show all roots approaching the broken face. The average of the count on either side of the break was then converted to a count cm^{-2}. This intersect method was similar to that of Drew & Slaker (1980) and Ellis and Barnes (1980). The number of roots per unit area that were intersected at horizontal breaks were calibrated against the root weights found between the breaks per unit volume of soil.

A selection of samples from all depths were washed and roots were collected on a 250 μm sieve. Non-root material was picked out from samples and discarded. Material recovered by this technique was shown to be almost entirely living roots. This was checked using congo red staining (Ward et al., 1978). Only a fraction less than 1 % of roots failed to take the stain. The technique is therefore assumed to underestimate, rather than overestimate, the weight of living roots.

Roots were dried at 70 °C and their ash-free weight was determined by loss on ignition at 550 °C. Those weights were calibrated with intersect counts. This calibration was performed for all the crops of the pasture species experiment. Weight density of roots in mg cm^{-3} (ρ_{rw}) was regressed on intersect counts cm^{-2} (n_r) of horizontal faces. The equations thus derived appear below;

Wheat	$\rho_{rw} = 0.129 \times (n_r)^{0.870}$	$n = 32,\ r^2 = 0.958$	(5.1)
Perennial ryegrass	$\rho_{rw} = 0.158 \times (n_r)^{0.871}$	$n = 22,\ r^2 = 0.972$	(5.2)
Tall fescue	$\rho_{rw} = 0.371 \times (n_r)^{0.906}$	$n = 26,\ r^2 = 0.980$	(5.3)

White clover	$\rho_{rw} = 0.124 \times (n_r)^{0.848}$	$n = 12,\ r^2 = 0.933$	(5.4)
Italian ryegrass	$\rho_{rw} = 0.149 \times (n_r)^{1.031}$	$n = 32,\ r^2 = 0.910$	(5.5)

These expressions are all geometric relationships. One of the reasons for such high regression coefficients was the inclusion of one pair of very small data points in each regression. This was legitimately included because it was checked that where there was no count at either end of a soil depth there was no weight of root recovered. Another reason is that the range of values was quite large as the high root densities of the 5-15 cm depth were included in the regression. A large proportion of the high density samples were used to maximise the accuracy of the top end of the regressions.

It was not possible to remotely assess the top 5 cm of the profile. This was because the technique involved counting roots either end of a depth of soil and such a count could not be made at the soil surface. Consequently, roots were washed out from every one of the 0-5 cm samples and weighed. The integrated weights to 100 cm depth were plotted against depth as shown in Figure 5.2 and total yields are given in Table 5.3.

5.1.4 Root yields in the pasture species experiment.

There was an outstanding yield of roots from tall fescue of 5.15 t ha^{-1} (see Table 5.3). This is partly explained by regression equation 5.3. Given that all the other geometric indexes were similar (with the possible exception of Italian ryegrass), the constant by which counts cm^{-2} (n_r) was multiplied in equation 5.3 was at least twice as large as any other constant. This suggests that a given length of tall fescue root was at least twice the weight of the same length of root from wheat, clover or the ryegrasses. The diameters of tall fescue roots were, from field observations, obviously greater than those of any other of the species used. However, this was not the subject of accurate investigation.

Table 5.3 Total root yields to 100 cm depth at anthesis (20/11/85) in the second season of the pasture species experiment.

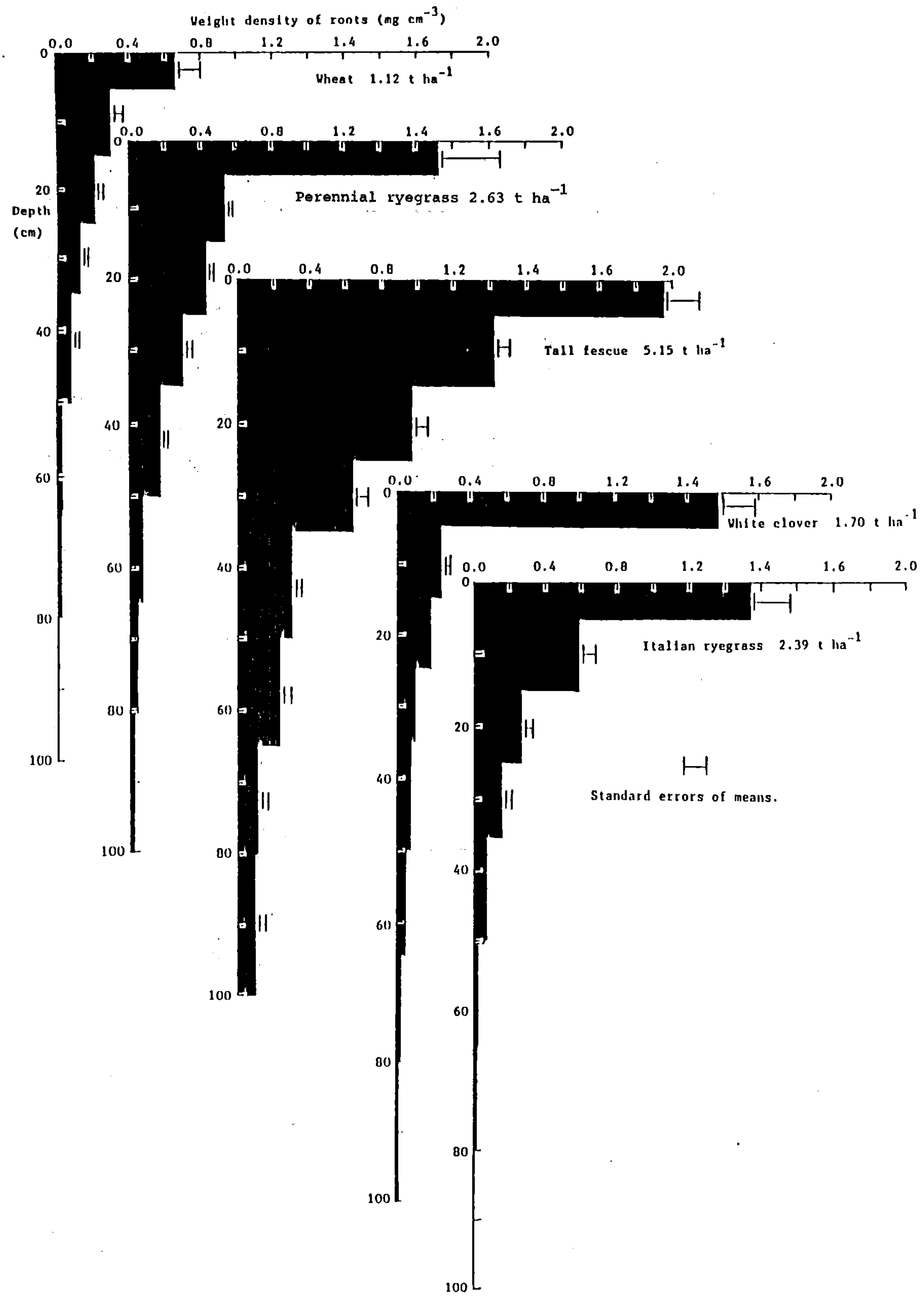
Crop treatment	Root yield to 1 m depth ($t\ ha^{-1}$)
Wheat	1.12 b
Perennial ryegrass	2.63 b
Tall fescue	5.15 a
White clover	1.70 b
Italian ryegrass	2.39 b

L.S.D. ($p<0.01$) = 1.65

Means NOT sharing letters were significantly different ($p<0.01$).

A notable feature of tall fescue was the large mass (600 kg ha^{-1}) of roots between 80 and 100 cm depth (Figure 5.2). From field observations, these clearly continued to penetrate below 100 cm. Perennial ryegrass and white clover also produced some roots to this depth. The two annual crops of wheat and Italian ryegrass failed in almost all replicates to produce roots to this depth.

Figure 5.2 Root weight density profiles for the pasture species experiment at anthesis in the second season.



The yield of wheat root weight was in the middle of the range (0.85-1.50 t ha^{-1}) reviewed by Gregory et al. (1978) from six publications. However, the yield of 1.12 t ha^{-1} found for this thesis is at the lower end of the range found by Barraclough & Leigh (1984) for high yielding wheat varieties in Britain (1.01-1.72 t ha^{-1}).

Root masses produced in the surface 5 cm are important to the resistance of soil to destructive forces. This zone is frequently the subject of diverse investigations of cropping effects on soil structure (Robinson & Jacques, 1958; Andrew, 1965; Low, 1972; Whitehead et al., 1975; Blevins et al., 1977; Lynch & Panting, 1980; Tisdall & Oades, 1980a; Imeson & Vis, 1984; Wood, 1985). Table 5.4 shows the root production in the surface 5 cm. The non-grazing management allowed all treatments, except for bare fallow and wheat, to achieve nearly total canopy closure. Under these conditions profuse surface rooting occurred, but this was not quantified specifically.

Table 5.4 Dry weight of roots in the top 5 cm of soil in the second season of the pasture species experiment (20/11/85).

Crop treatment	Root weight in top 5 cm. (t ha^{-1})
Wheat	0.33 b
Perennial ryegrass	0.87 ab
Tall fescue	1.18 a
White clover	0.90 a
Italian ryegrass	0.78 ab

L.S.D. ($p<0.01$) = 0.57

Means NOT sharing letters were significantly different ($p<0.01$).

It may be seen in Table 5.4 that wheat produced significantly less roots in the top 5 cm of soil than white clover or tall fescue. If this comparatively low production of wheat roots in this zone is typical then it may be concluded that this was a real crop effect of growing wheat which was quite undesirable from a soil structural point of view. The wheat root yield was not significantly different from zero or bare fallow.

On the other hand, it is notable that, despite the comparatively low total root yield of white clover in Table 5.3, the crop produced a large amount (54 %) of that root in the top 5 cm (Table 5.4). Coupled with this feature, the growth habit of white clover foliage might also be important in surface structural stability. This point will be returned to in Sections 5.1.6 and 5.2.2.

In summary, tall fescue produced the largest amount of roots in the top 5 cm. A group of treatments including white clover, perennial and Italian ryegrasses produced a similar weight, but a lesser amount than tall fescue. Wheat produced the least weight in the top 5 cm which was not significantly different from a bare fallow treatment ($p>0.01$). The size of the least significant difference indicates that high variability may have prevented other differences between crops from being detected.

The other profile zone of investigation in this study is the 5-15 cm zone. The root weights for this zone are shown in Table 5.5. The contribution of root weight to the soil at 5-15 cm showed definite differences between treatments. Numerically, the differences at 5-15 cm were similar to those of the top 5 cm, but the variability of the data-set was much smaller at 5-15 cm, as shown by the LSD values in Tables 5.4 and 5.5. All treatments were significantly greater than bare fallow or zero. Wheat and white clover yielded similarly and were the lowest of the treatments, about half the weight of the ryegrass~~e~~es and one fifth of the tall fescue weight. Tall fescue root weights in this zone were three times higher than both of the ryegrasses.

Table 5.5 Dry weights of roots at 5-15 cm depth in the second season of the pasture species experiment (20/11/85).

Crop treatment	Root weight at 5-15 cm. ($t\ ha^{-1}$)
Wheat	0.30 c
Perennial ryegrass	0.57 b
Tall fescue	1.53 a
White clover	0.25 c
Italian ryegrass	0.59 b

L.S.D. ($p<0.01$) = 0.19

Means NOT sharing letters were significantly different ($p<0.01$).

For tall fescue, it may be calculated that careful analysis of soil organic matter content might show a difference of 0.13 percentage points due to root weight alone compared with bare fallow at 5-15 cm. With other undetected residues organic matter from tall fescue might amount to twice this value (based on Gibbs, 1986), i.e. 0.26 percentage points before decomposition. This was not found to be the case because the variability of the organic matter data-set was too great to allow detection of such small differences (see Section 5.1.6).

5.1.5 Root yield of the tillage and cropping experiment.

The format of this experiment was described in Section 4.1. Root cores were taken at anthesis in both seasons of the experiment. The tillage and cropping experiment had two cultivation treatments, ploughing and direct-drilling. The only other difference between this and the pasture species experiment was the addition of 21 kg ha^{-1} of nitrogen in the first season and 40 kgN ha^{-1} in the second season, also prior to anthesis.

The same method as that described in Section 5.1.3 was used to estimate root weights. Four replicates, one from each plot, were taken for each treatment combination. The calibrations used for Italian ryegrass and wheat in the pasture species experiment were used. Some of the replication used to derive those equations (5.5 and 5.1) came from the tillage and cropping experiment. Yields were therefore calculated using equations 5.5 and 5.1 for Italian ryegrass and wheat. Table 5.6 shows the total root yield to 100 cm depth, top 5 cm weight and 5-15 cm weight for each season for each treatment combination.

No significant difference occurred between the two tillage treatments with respect to root production. This result was also found by Ellis & Barnes (1980) on a number of soil series in Britain. The results between the two seasons were also very similar. The only slight difference was a reduction in variability in the second season as shown by the lower least significant differences.

In both seasons, Italian ryegrass produced a significantly greater weight of roots in the top 5 cm, at 5-15 cm and in total to 100 cm depth. This may be interpreted as being a true crop difference between Italian ryegrass and wheat.

Table 5.6 Dry weights of roots produced at anthesis in the two seasons of the tillage and cropping experiment.

Treatment combination	Dry weight of roots ($t\ ha^{-1}$) Top 5 cm	5-15 cm	Total to 100 cm.
	6/11/1984		
PLIR	0.72 a	0.53 a	2.07 a
DDIR	0.58 a	0.45 a	1.81 a
PLW	0.19 b	0.22 b	0.87 b
DDW	0.21 b	0.23 b	0.83 b
L.S.D.($p<0.05$) =	0.23	0.10	0.36
	18/11/1985		
PLIR	0.71 a	0.53 a	2.08 a
DDIR	0.75 a	0.47 a	2.14 a
PLW	0.23 b	0.24 b	0.94 b
DDW	0.26 b	0.24 b	0.95 b
L.S.D.($p<0.05$) =	0.15	0.07	0.29

Means NOT sharing letters within vertical data-sets were significantly different ($p<0.05$).

PLIR = PLoughed Italian Ryegrass PLW = PLoughed Wheat.
DDIR = Direct-Drilled Italian Ryegrass DDW = Direct-drilled Wheat.

The weights recorded on this tillage and cropping experiment were consistently, but not significantly ($p>0.05$), lower than the results for the same two crops in the pasture species experiment. Results may be assumed to be similar, and so the profile distributions have not been drawn for the tillage and cropping experiment.

5.1.6 Organic matter levels in the silt loam survey.

Four years of history of crops grown, cultivations and residue management used for all sites is recorded in Appendix Three. Only those organic matter values which were from field experiments or those values which show some specific effect are presented in this section. Organic matter contents of field samples were found using the method described in Section 4.4.6.

The pasture species experiment was sampled at 0-2 cm and 5-15 cm depths as part of the silt loam survey (sites 12-19 and 17-34). The results at the end of the second season (sites 27-34) are shown in Table 5.7.

Table 5.7 Organic matter content at 0-2 cm and 5-15 cm depths in the pasture species experiment at the end of the second season (% w/w).

Crop treatment	0-2 cm	5-15 cm
Wheat	5.9 c	5.1 d
Fallow	5.8 c	5.2 d
Perennial ryegrass	6.0 c	5.4 d
Tall fescue	6.3 bc	5.5 d
White clover	7.0 a	5.4 d
Per. regrass/W.clover	5.7 c	5.3 d
Tall fescue/W.clover	6.6 ab	5.5 d
Italian ryegrass	5.9 c	5.4 d
L.S.D.($p<0.01$) =	0.65	0.39

Means NOT sharing letters within vertical dat-sets were significantly different ($p<0.01$).

It may be seen from the surface 2 cm values that white clover and tall fescue treatments were associated with significantly different ($p<0.01$) organic matter levels compared with any other treatments. This may be explained by the large weight of roots produced (Table 5.4).

However, the fact that organic matter was greatest under white clover rather than tall fescue is not explained by the values for root weight in Table 5.4.

The probable explanation for this reversal in ranking of organic matter values relates to the growth habit of clover. The stem rhizomes which grow over the soil surface and into the topsoil would have been included (if they were not green) in the organic matter estimate but not in the root weight estimate. Tall fescue did not produce underground stems, nor did any of the other grasses, and so only roots would have been included in the organic matter estimate for that grass.

All treatments other than tall fescue and white clover were not significantly different from the bare fallow treatment. Therefore, the highest production of organic matter at the 0-2 cm depth of soil were made by white clover and tall fescue.

At 5-15 cm, there was no significant difference between any of the treatments. The expected difference discussed in Section 5.1.4 between tall fescue and other treatments could not be detected with any confidence. The highest organic matter values were indeed associated with tall fescue, but all differences between treatment means were within the limits of the least significant difference.

The five sites visited at Cartwheels, Rangiora, (sites 7-11) gave the organic matter values that are shown in Table 5.8. Again, full histories of these sites may be found in Appendix Three. The essential features were at least seven years of direct drilling with light stocking and continuous cropping, except for site 11. Site 11 was a four year old stocked pasture that had been ploughed four years previously.

Table 5.8 Organic matter content at 0-2 cm and 5-15 cm depths at Cartwheels, Rangiora (sites 7-11) (% w/w).

Site	Cropping	0-2 cm	5-15 cm
7	5 yrs Wheat, Barley	7.5 ab	4.7 bc
8	W.c., 4 yrs Wheat, P.ryegrass	6.6 b	4.4 c
9	W.c., 3 yrs Wheat, W.c., Wheat	7.6 a	5.0 b
10	Wheat, W.c, 3 yrs Wheat, W.c.	8.4 a	4.9 b
11	Wheat, Long ley/pasture	8.1 a	5.5 a
	L.S.D. ($p<0.01$) =	0.93	0.44

Means NOT sharing letter within vertical data-sets were significantly different ($p<0.01$). W.c. = white clover

Despite its prior arable history, the four years of pasture on site 11 were associated with the highest organic matter value at 5-15 cm. At 0-2 cm the organic matter content of site 11 was not significantly different from the highest value at site 10. It was notable that the clover sward on site 10 which showed the highest organic matter value for the top 2 cm of soil, rather as it did in the pasture species experiment. Sites 7 and 8 had the longest prior history of unbroken cereal cropping and had the lowest organic matter values at 0-2 cm and 5-15 cm.

5.2 CULTIVATION EFFECTS ON ORGANIC MATTER.

5.2.1 Review of cultivation effects on organic matter status.

Accumulation of organic matter in the top 5 cm of soil has been observed when soils with a history of ploughing have been subsequently direct-drilled (Blevins et al., 1977). In the work of Blevins et al., the organic matter content of the 5-15 cm zone was greater under repeated ploughing than under direct drilling. This occurred because the surface accumulation was repeatedly incorporated and mixed into the topsoil. The total organic matter of the soil was larger under direct drilling than ploughing, but markedly concentrated near the soil surface.

That organic matter accumulates when disturbance is minimised compared with repeated disturbance, such as cultivation, was shown by Rovira & Greacen (1957) and Brown et al. (1965). These workers measured oxygen consumption of the soil and observed an increase in disturbed soil compared with undisturbed soil. It was concluded that disturbance, such as cultivation, increased respiration rate in the soil and thus reduced organic matter at a faster rate. Cheshire (1979) concluded that reduction in disturbance/cultivation resulted in greater organic matter residues.

Lynch & Panting (1980) showed that biomass increased in the top 5 cm of soil under direct-drilling compared with ploughing. They thought this might have occurred because there was more root weight produced at that depth under direct drilling than ploughing. Lynch & Panting also estimated that 3.5 t ha^{-1} a^{-1} of organic carbon was input to the top 5 cm of soil. The components of this figure are given in Table 5.9

Table 5.9 Suggested components of organic carbon inputs to the top 5 cm of soil under an arable wheat crop from Lynch & Panting (1980).

Root decomposition	400 kg ha^{-1} a^{-1}
Root exudation	240 " " "
Straw residues	2800 " " "
Autotrophic microbes	100 " " "
TOTAL	3540 " " "

Note that straw residues were an important proportion of returns. Where straw residues are burned, only one fifth of the above total would be returned to the top 5 cm.

In North Australia, Wood (1985) found that repeated cultivation for sugar cane production had reduced organic carbon levels in the top 10 cm of soil from 1.5 to 0.7 % in 15 years. This was associated with a significant deterioration in water availability and nutrient status of the soil in question.

5.2.2 Cultivation and soil organic matter of survey sites.

The major effects of cultivation have been established as twofold; i) organic matter at the soil surface is incorporated and mixed to the depth of cultivation (Blevins *et al.*, 1977), and ii) more rapid decomposition occurs due to disturbance (Rovira & Graecen, 1957; Brown *et al.*, 1965). To illustrate the greater concentration of organic matter at the surface of undisturbed soil, the following Organic Matter Quotient (q_{om}) has been used;

$$q_{om} = \frac{M_{t(0-2)}}{M_{t(5-15)}} \tag{5.6}$$

where $M_{t(0-2)}$ is the organic matter content at 0-2 cm and $M_{t(5-15)}$ is the organic matter content at 5-15 cm depth.

Using the q_{om}, a useful appraisal of the gradient between the surface organic matter concentration and that at 5-15 cm may be made. Table 5.10 shows some comparable survey sites, including the tillage and cropping experiment (40-43) which all had two years of their tillage treatments.

Table 5.10 Organic matter quotients for direct-drilled and ploughed sites after two years of treatments.

Ploughed and worked.				Direct drilled.			
Site no.	% OM 0-2 cm	% OM 5-15 cm	q_{om}	Site no.	% OM 0-2 cm	% OM 5-15 cm	q_{om}
1 PLF	6.2	6.4	0.97	2 DDF	7.5	5.9	1.27
3 PLW	6.4	6.4	1.00	4 DDW	7.7	6.2	1.24
5 PLPR	7.0	6.4	1.09	6 DDPR	8.8	6.2	1.42
40 PLIR	5.6	5.2	1.08	41 DDIR	6.7	5.0	1.34
42 PLW	5.5	5.0	1.10	43 DDW	5.7	5.0	1.14

F = Fallow; PR = Perennial ryegrass;
W = Wheat; IR = Italian ryegrass.

Sites 7-10 at Cartwheels, Rangiora had been direct-drilled for seven years and had q_{om} values of 1.60, 1.50, 1.52 and 1.71 respectively. With time, the quotient may increase for soils under direct-drilling. After just two years the q_{om} values for direct-drilled soils were consistently greater than for ploughed soils.

The permanent pasture next to the tillage and cropping experiment (site 24) had an q_{om} value of only 1.16 after at least six years of pasture. Site 11 at Rangiora had an q_{om} value of 1.47 after four years since ploughing, which was lower than neighbouring direct-drilled arable sites. It would appear from these results that under pasture organic matter levels were not only increased at the surface, but more generally in the topsoil. Thus the q_{om} was less for an older pasture than direct-drilled arable sites (see Table 5.10).

To summarise, ploughed soils had q_{om} values close to unity and direct-drilled arable soils had higher q_{om} values indicating a strong concentration of organic matter at the soil surface. Pasture had larger overall amounts of organic matter, but lower q_{om} values than direct-drilled arable soils because a of more general increase in organic matter in the topsoil.

5.2.3 Other effects on organic matter status.

Deliberate additions of organic matter to soil are frequently studied. Christensen (1986) experimented with incorporating straw into soil with a low aggregation potential and observed an improvement in aggregation. Edwards & Lofty (1979) studied different methods of straw disposal and found that earthworm numbers improved with the retention of greater amounts of organic matter as straw. The fate of residues was also important to microbial biomass (Lynch & Panting, 1980; see Section 5.2.1)

Mulching rather than burning residues has been adopted in large areas of the U.S.A. to reduce wind erosion (Allmaras & Dowdy, 1985). This also had the effect of increasing organic matter levels at the soil surface which Lynch & Panting (1980) observed. From the work of Lynch & Panting it may be calculated that burning of arable residues may reduce organic matter returns to the top 5 cm of soil by 80 % compared with mulching. The impact of this on soil organisms will be discussed in Chapter Six.

The role of earthworms in the decomposition process was addressed by Stout _et al._ (1976). By burying litter and finely mixing organic matter and mineral soil, decomposition is accelerated in worm cast material due to enhanced microbial activity (Edwards & Lofty, 1977; Lee, 1985). Whilst in the short term this may result in more rapid loss of organic matter, in the longer term the faster cycling of nutrients tends to increase the level of organic matter in a soil with earthworms (Stockdill & Cossens, 1966).

Burial of organic matter by earthworms also changes the profile distribution of organic matter (Stockdill & Cossens, 1966). Lee (1985) has reviewed literature on this effect. Certain species have different effects on the depth to which organic matter is incorporated. Also of significance is the association of organic matter with the walls of earthworm burrows and the possible effect of this association on pore stability. These burrows are important macropores from a structural view point.

Reid & Goss (1982) showed that the very presence of roots might inhibit decomposition of organic matter already present in the soil. Various mechanisms for this were discussed. The effect means that not only is there organic matter production by roots, but their presence may also slow down decomposition of other organic matter.

Garwood <u>et al.</u> (1972) showed that macro-organic matter levels in the top 12 cm of soil varied for different pasture management. Those results appear in Table 5.11 below.

Table 5.11 Macro-organic matter in the top 12 cm of soil under differently managed three year leys from Garwood et al. (1972).

Management of ley.	Macro-organic matter $t\ ha^{-1}\ a^{-1}$
Infrequently grazed	8.74 a
Hay + after grazing	8.56 a
Frequent grazing	8.01 b
Four cuts of herbage	7.66 c
Arable (for comparison)	4.38
Means NOT sharing letters were significantly different ($p<0.05$).	

Frequent grazing limited plant growth by reducing ground cover, and cutting and removing herbage prevented litter from being returned to the soil. That stock grazing a ley may have an effect on organic matter levels compared with cutting and removing herbage for hay was also demonstrated by Clement & Williams (1964). Much of the organic matter was returned to the soil as dung, or trodden into the soil surface as litter under grazing, whereas greatly reduced returns occurred when herbage was cut for hay.

Williams (1960) showed that the removal of nutrients in hay compared with their return by grazing could adversely affect a subsequent crop of wheat. He also found that large root masses were not necessarily useful to subsequent crops if their nitrogen content was low.

5.3 SUMMARY OF ROOT AND ORGANIC MATTER INPUTS.

The actual structuring and stabilising effects of roots have not been addressed. No direct study of structuring was made, but it would appear that tall fescue roots were capable of penetrating to a depth of at least 100 cm with greater frequency than other grasses in the pasture species experiment. It might therefore be expected that, following decay, those roots would provide continuous exploitable biopores to a depth of at least 100 cm for subsequent crops. The question of effects on aggregate stability will be addressed in Chapter Nine.

In terms of root weight added to the soils studied, there were appreciable differences between crop species. This was true not only of total yields of root weight, but also of the positioning in the soil profile where those yields occurred. The positioning and total yield of roots suggested that wheat, as a crop, has a less favourable rooting habit with respect to soil structure than grasses.

Such an approach also revealed that, under an undisturbed or direct-drilling regime, white clover was highly beneficial to soil structure by virtue of its organic matter concentration near the soil surface. Tall fescue was revealed to be more generally useful throughout the profile.

Little or no effect of cultivation on root weight formation or distribution was observed. However, cultivation was observed to alter the distribution of accumulated organic matter as shown by the comparison of surface concentrations with those at 5-15 cm depth using an Organic Matter Quotient (q_{om}).

CHAPTER SIX

EARTHWORM POPULATIONS

Bouché and Gardner (1984) stated that any approach to modelling earthworm ecology begins with a population estimate. This chapter shows how earthworm populations react to the Canterbury Plains environment and the effects of agricultural management. This is a necessary precursor to the following chapter on burrowing activity of populations.

An outline of the major earthworm ecological classifications is given. It is necessary to understand the feeding and burrowing strategies of different species in order to predict the effect on soil structure of any given species.

The effects of crop and soil management on populations are reviewed. Some results of observed management effects on Canterbury populations which were studied for this thesis are given. The aim of this work is to improve predictions of earthworm populations given a certain set of management decisions. With greater understanding of population dynamics, the effect of earthworms on soil structure may be more readily predicted.

6.1 ECOLOGY OF LUMBRICID EARTHWORMS ON THE PLAINS.

The native earthworms of the Canterbury Plains are of the family Megascolecidae which is part of the superfamily Megascolecidea. This superfamily is found in Australia and the Pacific region. Consequently, Bouché (1983) estimated that the superfamily dates back to the Mezozoic era when all these regions were still part of Gondwanaland.

When Europeans arrived they changed the plains environment from that described in Section 3.2.2 by ploughing, sowing pastures and arable cropping. Lumbricid earthworms which came with them, both by design and by accident, became established in settled land. We now have the situation where agricultural soils contain lumbricids and native vegetation supports megascolecids (Lee, 1961).

6.1.1 Niches of lumbricid species.

The three main habitats (niches) of earthworms in general were described by Bouché (1975) and reviewed by Sims & Gerard (1985). These categories have made the work of linking ecology with burrowing habit quite straight forward. However, it is rare for any one species of earthworm to fit into one niche description only.

A diagram showing typical burrowing patterns of earthworms in the three major niche categories appears in Figure 7.3 and is discussed in 7.1.3. There follows a description of the three major niches with examples from lumbricids found in New Zealand.

6.1.1.1 Epigeic earthworms.

These are litter dwelling species. They live in a high risk habitat and may move rapidly to evade predators. They are pigmented, tend to be small in size, and do not enter a diapause condition to avoid adverse environmental conditions. Epigeic worms feed on surface litter and detritus which is termed mesophagous. Three subcategories were described by Bouché (1975);

(i) straminicole species (leaf mould worms) which compete with deep burrowing worms for food in mull soils.

(ii) corticole species which are particularly adapted to live in tree trunks, compost and mor soils.

(iii) pholeophilic species which live in soil burrows of other species, especially those of deep burrowing species.

Note that true epigeic species do not burrow in the soil. Some examples of predominantly epigiec lumbricid species in New Zealand are Eisenia fetida (Sav) (a corticole species) and Lumbricus rubellus (Hoff) (Lee, 1959; 1985; Easton, 1983).

6.1.1.2 Endogeic earthworms.

Endogeic species live within and feed within the soil which is termed microphagous. This is a comparatively low risk habitat as the soil environment changes less rapidly than the surface and predators are fewer. Thus endogeic species are comparatively sluggish, may be a wide range of sizes and lack pigmentation. They sometimes have the ability to enter a diapause condition known as aestivation.

This sort of earthworm appears to burrow randomly or in a predominantly horizontal direction. Much soil is ingested and egested below the surface. Bouché (1975) specified two pairs of subcategories by feeding habit and by position in the soil profile as follows;

(i) geophages which eat only mineral soil and the organic matter consequently ingested which tends to be of a highly decomposed amorphous nature.

(ii) saprorhizophages which eat dead plant and microbial material by burrowing in the root zone.

(i) epiendogeic worms which live in the topsoil close to the surface or within the A horizon. They may be saprorhizophagous or geophagous.

(ii) hypoendogeic worms which live in subsoils with low organic matter. They are often large and sluggish.

Note that true endogeic species do not feed at the soil surface, nor do they create deep vertical burrows connected with the surface. New Zealand lumbricid species predominantly in the endogeic category include Octolasion Cyaneum (Sav) (hypoendogeic/geophagous) Aporrectodea caliginosa (Sav), A. trapezoides (Sav) and Allolobophora chlorotica (Sav) (all epiendogeic and saprorhizophagous) (Lee, 1959; 1985; Easton, 1983).

6.1.1.3 Anecic earthworms

Species of this niche are the comparatively well known deep burrowers which feed at the surface (macrophagous). These worms are pigmented, tend to be large in size and are physiologically adapted for rapid withdrawal into burrows from the surface as well as for deep burrowing. This is a niche of intermediate risk between the epigeic and endogeic niches. Diapause is common, and sometimes obligatory.

Burrows may descend 5 or 6 m in extreme cases. Burrows ramify near the surface and tend to be lined with organic matter pulled down from the surface. Soil is egested up onto the surface or into walls of burrows with litter, microorganisms and mineral matter. New Zealand examples of predominantly anecic species are *Lumbricus terrestris* (Lin) and *Aporrectodea longa* (Ude) (Lee, 1959; 1985; Easton, 1983).

Work by Piearce (1978) confirmed the feeding categories for *A. longa*, *A. caliginosa*, *Allolobophora chlorotica* and *L. rubellus* as outlined above. Piearce made direct observation of the gut contents of these and other species in the autumn of 1970 from permanent pasture in Wales in Great Britain.

6.1.2 Displacement of native species.

Lee (1961) described a typical transition from native New Zealand bush to pasture. On clearing the native vegetation the litter layer declined and native megascolecid epigiec and endogeic species died out as their food source was exhausted. Hypoendogeic (subsoil) species persisted.

A period occurred during new pasture establishment when no topsoil species were present. Subsequently lumbricid species, *Lumbricus rubellus* and *Aporrectodea caliginosa*, colonised the area with the hypoendogeic megascolecid species still present.

Lee (1961) also stated that such a transition is highly probable in most cases where land is sown to pasture or arable crops out of native vegetation. Lumbricid species invade where megascolecids have died out through land management effects; the two families do not compete for food or space, neither do they predate upon one another in such circumstances.

Thus there is a clear difference between habitats and earthworm families. New Zealand megascolecids do not survive under the introduced European agricultural systems, but lumbricids are well suited. Studies of earthworms of New Zealand agricultural soils are consequently (predominantly) studies of lumbricids.

6.1.3 Climate effects on populations

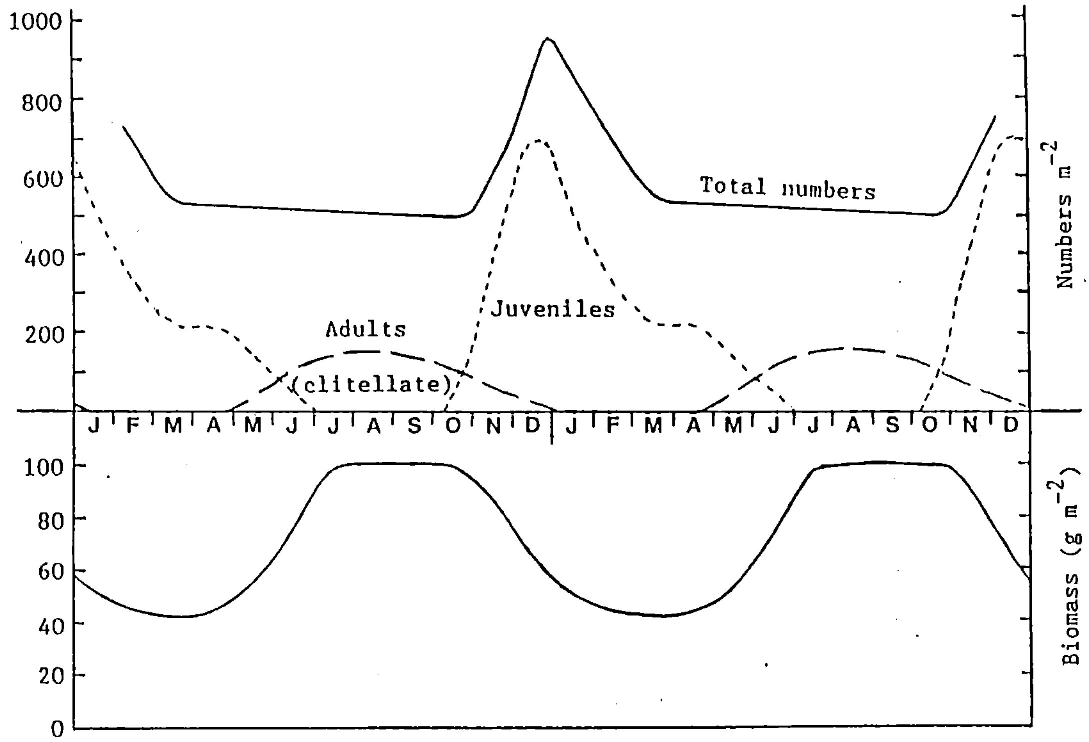
The two major environmental effects on earthworm activity are moisture availability and temperature (Nordström, 1975). Barley (1959c) found that the period of activity of Eisenia rosea and Aporrectodea caliginosa was similar to the growing period of clover*, which was from April to October near Adelaide in Australia. McColl (1984) showed a period of activity from April to October in central New Zealand which was closely related to soil moisture content. Her measurements were of populations in the top 20 cm which probably did not recover worms aestivating at greater depths through the summer. Also in New Zealand, Sharpley & Syers (1977) found that under permanent pasture A. caliginosa produced casts above the surface from April to September. They also found that maximum cast production occurred when the soil gravimetric water content was above 21 % and the temperature was greater than 10 °C.

* Trifolium subterraneum L.

Nordström (1975), in Sweden, found that the Aporrectodea genus was active at moisture potentials between saturation and -3.2 bar and temperatures between 0 and 20 °C. When the soil froze, worms burrowed deeper and became quiescent or went into a state of diapause, a similar reaction to that for drought.

The general population changes through the year for A. caliginosa under pasture in the north of the North Island of New Zealand is shown in Figure 6.1. From year to year there would be large deviations from this general pattern shown by Martin (1978) due mainly to temperature and rainfall fluctuations about the long term mean.

Figure 6.1 Annual population and biomass cycle of earthworms under New Zealand pasture from Martin (1978).



6.2 OBSERVED SPECIES DISTRIBUTION.

It is necessary to know which species of earthworms are present in soils in order to predict the pattern and quantity of burrowing in given environmental conditions. This section discusses the measurement technique employed for assessing populations and the qualitative results of species distribution on the sites studied are given.

6.2.1 Sampling technique.

The method used to sample earthworms was by direct hand sorting, usually in the field. Collected worms were counted and identified by species, and categorised as juvenile (newly hatched), immature or adult (clitellate). The area of samples was 23 x 23 cm, which is a spade width, a similar method to that used by Martin (1978) and McColl (1985). Numbers were multipied by 19 to give numbers m^{-2}. The depth of sampling was to a point where no evidence of previous earthworm activity could be detected. This was often 30 to 40 cm depth.

Although time consuming, this method allows the operator to get a feel for where the worms are in the profile and what soil features they are associated with. It is also possible to get a feel for the rooting pattern and structure of the soil. Complete recovery of aestivated worms was possible using hand sorting to 30 or 40 cm. This is only true because there were no anecic worms present in the soils studied.

Satchell (1969) reviewed sampling techniques and concluded that hand sorting was a poor recoverer of juveniles and small species. No small species were present and so only juveniles presented difficulty.

Satchell also concluded that using the expellent/excitant formalin (methanal) method was not very efficient for endogeic worms (horizontal burrowers) or aestivated worms.

For their International Biological Program (PBI), Bouché & Gardner (1984) concluded that a comprehensive technique was to use both ethological (expellent) and physical (hand sorting) techniques in order to recover epigeic/anecic and endogeic/aestivated worms respectively.

Satchell (1969) showed that 25 x 25 cm samples (approximately that used in this study) were better for hand sorting than larger samples because they were less tedious to sort. Operator fatigue is one of the largest sources of error in the direct hand sorting technique.

Because of seasonal fluctuations in earthworm populations shown by Waters (1955b), Nordström (1975), Barley (1959c), Martin (1978) and McColl (1984), there are optimum times of the year for sampling. In New Zealand this is usually in August. This is because worms are usually active and large (Martin, 1978). However, fluctuations in weather from year to year make this unreliable. Constraints of this study meant that population estimates were made at sub-optimal times. To try to ameliorate the effects of bad timing, sampling was done four days after infiltration rate measurements to allow for reactivation of quiescent individuals.

The time of year, or more specifically the environmental conditions at the time of sampling may have had an important effect on earthworm numbers recovered. In an experiment conducted to test the advisability of prewetting before sampling for earthworms, it was found that numbers recovered were about half in dry soil compared with prewetted soil. In addition, the variability was greater in the dry soil. In some sites the numbers of earthworms would have been a greater underestimate than others on account of some dying out (especially L. rubellus) as the soil dried.

Martin (1978) found that plots of 3 x 5 m in dimension were not large enough to prevent migration from masking treatment differences. In the Netherlands, Hoogerkamp et al. (1983) found that A. caliginosa was capable of colonising new land at a rate of 9 m y^{-1} which indicates the average annual distance of travel of this species. Stockdill (1982) reported a migration speed of 10 m y^{-1} in New Zealand soils. This was important because plots of the pasture species experiment were only 3 x 6 m in dimension.

6.2.2 Species present

The species found in the agricultural soils studied for this thesis were all lumbricids as found by Lee (1961). No anecic species were found, only epigeic and endogeic species. As mentioned in 6.2.1, no evidence of earthworms working below 30 to 40 cm was found which supports the observation that deep burrowers were absent. Table 6.1 shows the species found and their niche characteristics.

Table 6.1 Lumbricid species of Canterbury Plains soils studied.

Lumbricus rubellus (Hoff)	endoepigeic habitat
Aporrectodea caliginosa (Sav)	epiendogeic habitat
Aporrectodea trapezoides (Sav)	epiendogeic habitat
Octolasion cyaneum (Sav)	(hypo)endogeic habitat

It is thought that all these species were introduced by accident with ships' ballast and with exotic flora from Great Britain (Lee, 1961). These species are peregrine and can be found in various parts of the world due to European man's movements. Similar species are found in Australia for the same reasons (Barley, 1959a).

6.2.3 Spatial distribution of species.

A. caliginosa was found on all sites studied for this thesis except two under native vegetation and one where earthworms had died out altogether under a fallow site due to a chemical accident (site 39). All the productive agricultural soils contained A. caliginosa. A complete data-set may be found in Appendix Six.

With the exception of four sites, A. trapezoides was found everywhere that A. caliginosa was found. The former species is supposed to be a close relative of the latter (Easton, 1983), so such a finding is not surprising. The only exception to this general trend was one area suffering from heavy traffic, where the former species was neither found in the traffic areas nor the less disturbed areas near by (sites 25, 26, 35 & 36). Therefore it is assumed that management prior to the traffic event was responsible for the former species dying out.

L. rubellus was found only in agricultural soils under permanent meadow pasture and a few localised sites. (The predominantly epigeic habitat of this species makes it highly intolerant of cultivations and the removal of litter (Lee, 1985). By "meadow" pasture, it is meant that the sown grass/clover sward was far from pure and contained other grasses and flowering plants.

For some reason L. rubellus was found in the first and second years of the pasture species experiment (sites 12-14 and 27 - 34) but not in an adjacent experiment (sites 40 - 43) nor under permanent pasture only 30 m away (site 24). This is still unexplained, unless the clover/wheat rotation either side of the experimental area allowed the species to proliferate and subsequently migrate onto the experimental area. Watkin & Wheeler (1966) showed that the presence of clover in pasture swards favoured L. rubellus, particularly in stocked pasture where there was animal dung returned. The highest concentration in the pasture species experiment was 180 m^{-2} in the pure clover sward plots (see Table 6.2). The second and fourth highest were on grass/clover plots. Maybe there was a link between high nitrogen litter and the incidence of L. rubellus, but populations must have depended on a local source of innoculum since other sites growing clover did not support L. rubellus, such as the pure clover sward of site 9.

Table 6.2 Lumbricus rubellus populations in the second year of the pasture species experiment.

Treatment (crop)	Maturity Immature	Mature	Total (m^{-2})
Wheat	50	20	70 ab
Fallow	30	20	50 b
Perennial Ryegrass	50	20	70 ab
Tall Fescue	40	10	50 b
White Clover	80	100	180 a
Per. Ryegrass/W. Clover	60	20	80 ab
Tall Fescue/W. Clover	40	60	100 ab
Italian Ryegrass	70	20	90 ab
			LSD($P<0.01$) = 120

Means NOT sharing letters were significantly different ($p<0.01$).

On comparable Lucerne swards (sites 37 & 38) L.rubellus was present on both sites. In the unstocked treatment there were fewer than in the stocked treatment. No set pattern of the occurrance of L. rubellus can be deduced from these observations.

Octolasion cyaneum was found even more sporadically than L.rubellus. The former species was found in appreciable numbers (90 to 200 m^{-2}) at the two "meadow" pasture sites where L. rubellus was found (sites 22 & 23). The only other sighting was on an experimental area with a history of sheep stocked pasture (sites 1 - 6).

It would seem from this that the incidence of O. cyaneum is highly localised. Being a true endogeic species, its ability to migrate over the soil surface would probably be limited compared with L. rubellus, A. caliginosa and A. trapezoides.

6.3 MANAGEMENT EFFECTS ON EARTHWORM POPULATIONS

Having established that the majority of sites support mostly A. caliginosa and A. trapezoides, the next step towards modelling burrowing is a numerical evaluation of of earthworm populations. Many factors have been shown to affect populations such as organic matter returns, cultivation practices, crop choice and the use of toxic substances in plant protection. These different effects have all been documented in the course of this study and are presented in this section. Literature is reviewed with respect to management effects on populations.

6.3.1 Effect of crop choice

In "crop choice", the entire management option is included. Low (1972) showed that long term (100 years) arable cropping supported fewer earthworms (20 m^{-2}) than an old (120 years) grassland site which supported 125 to 185 m^{-2}. When arable cropping occurred on an old pasture site, after the third year numbers had dropped to between 40 and 75 m^{-2}. No species breakdown was given, but it is probable that many of the worms would have been anecic, large worms, at least in the pasture (Edwards & Lofty, 1977). It is important to note that "arable" in this case meant annual ploughing and straw burning, as well as growing wheat.

One of the few studies to specifically address the effects of crops themselves on earthworms was conducted by Lofs-Holmin (1983), sequentially sampling over an eight year period. The populations consisted of Lumbricus terrestris, A. caliginosa and L. rubellus with small numbers of a few other species. Lofs-Holmin made the important point that populations at a given time tend to reflect the crop and cultivation management of the previous, not current, year. It is thus important to accurately know the previous history of a soil being sampled.

Lofs-Holmin (1983) showed that the only crop effect that could be measured was after rape straw was ploughed in. Numbers of *A. caliginosa* in particular rose, but so did *L. terrestris* numbers. The overall management effect of growing sugar beet was shown to be deleterious to earthworm populations because roots were harvested and organic matter returns were low (as shown in Table 5.1). This effect was also found by Edwards (1983) who found that root cropping was more deleterious to earthworm populations than cereal cropping, but less than bare fallow.

Waters (1955a) showed that numbers and weights of earthworms were directly related over a four year period to herbage production of permanent pasture. Waters also concluded that activity was related to the availablity of dead roots, which may be further evidence of the saprorhizophagous feeding habit of *A. caliginosa*. Barley (1959a) showed that a relationship existed between harvested yield and earthworm biomass such that 10 t ha^{-1} of herbage was associated with a biomass of 800 kg ha^{-1} of the worms *Eisenia rosea* and *A. caliginosa* in Australia, near Adelaide.

It was shown by Watkin & Wheeler (1966) that in New Zealand a pure grass sward supported a dominance of *A. caliginosa* whereas under a clover/grass sward *L. rubellus* dominated. Where animal dung was present, *L. rubellus* was still more dominant, an often observed fact that has earned the species the nick-name of the "dung worm".

In other work Lofs-Holmin (unpublished) fed juvenile A. caliginosa with pieces of barley (Hordeum distichum), Lucerne, and Meadow Fescue (Festuca pratensis). Worms gained weight faster on Meadow Fescue roots than Lucerne roots and shoots, than Meadow Fescue shoots. Barley (1959b) found that A. caliginosa gained weight on farmyard manure (FYM), maintained weight on clover and lost weight on Phalaris (Phalaris tuberosa) leaves and roots.

Most other work, whether reported as "crop" effect or not, has been a question of integrated management practice, rather than an effect of the crop itself. In a field experiment that was sampled for this thesis, a difference between direct-drilling and ploughing was observed, but the major trend was with the crop effect. That experiment is listed as sites 1-6 inclusive in Appendix Three. There were six treatment combinations: two cultivation treatments and three crop treatments as shown in Table 6.3.

Table 6.3 Cultivation and crop effects on earthworm populations after two years.

Cultivation Crop	Ploughed	Direct-drilled
	(earthworms m^{-2})	
Fallow	300 c	830 abc
Wheat	600 bc	950 ab
Peren. Ryegrass	1340 a	1370 a

LSD($p<0.05$) = 560

Means NOT sharing letters were significantly different ($p<0.05$).

The higher than usual populations in this experiment were probably due to the unusual history of the site. The land in question had been in permanent pasture and fertility had been concentrated in the experimental area by feeding stock there during the previous winter. The population of worms was thus abnormally high. Results showed a trend of decreasing earthworm populations in the order perennial ryegrass > wheat > fallow.

Fallow ground gave very variable results. In Table 6.3 high populations were found because of the high fertility history of those sites. In the pasture species experiment (sites 13 & 28) unusually high populations were found under bare fallow compared with growing wheat or grasses. These values may be seen in Table 6.4.

Table 6.4 Earthworm populations for two seasons of the pasture species experiment.

(earthworms m^{-2})

Crop	Season one	Season two
Wheat	450 abc	280 a
Fallow	570 a	400 a
Perennial Ryegrass	270 bc	270 a
Tall Fescue	200 c	240 a
White Clover	530 ab	340 a
P. Ryegrass/W. Clover	400 abc	270 a
Tall Fescue/W. Clover	270 bc	290 a
Italian Ryegrass	400 abc	250 a
	LSD($p<0.01$) = 270	LSD($p<0.01$) = 210

Means NOT sharing letters within vertical data-sets were significantly different ($p<0.01$).

It is important to note from Figure 4.2 that the pasture species experiment plots were only 3 x 6 m which were not large enough to be free of migration effects (Martin, 1978). One explanation for the consistently higher numbers under bare fallow over the two seasons would be that the soil moisture content was higher for longer periods. This would have allowed an extended season of activity which may have allowed an increase in population. Nevertheless, because this increase occurred in the first year, migration may have been an important factor. The high variability of values in this comparison meant that differences were of little significance.

Robinson (1955) found a significantly higher number of earthworms under white clover and perennial ryegrass treatments compared with bare fallow, cocksfoot, chewings fescue and red clover treatments. His findings were not supported by work for this thesis.

It may be concluded that little or no crop effect on earthworm populations was observed. It is possible that the bare fallow treatment had a temporary, positive effect on populations despite the convention that numbers decline under bare fallow. The results obtained in study for this thesis were inconclusive.

6.3.2 Residue management.

Lofs-Holmin (1983) showed that adding Farmyard Manure (FYM) had a large influence on increasing numbers of all worms present. The effect was seen one and a half years after the event. The long term mechanism affecting earthworm populations is in the number of cocoons that the stimulated population leaves for the following year (Edwards & Lofty, 1977).

When FYM was left on the surface in the work of Lofs-Holmin (1983), epianecic (L. terrestris) and endoepigeic species (L. rubellus) were the major responders because they choose to feed at the surface. When FYM was incorporated A. caliginosa (epiendogeic) responded most. The latter observation was also made by Barley (1959b). Numbers of A. caliginosa were doubled due to an application of FYM at 4 t ha^{-1} in a study by Edwards (1980).

Lofs-Holmin (unpublished) found that reducing particle size of organic matter returns by 5 times doubled the rate of weight gain on barley straw. A comparison of straw management was also made by Edwards & Lofty (1979). The results of that study and the treatments appear in Table 6.5, below.

Table 6.5 Earthworm populations of A. caliginosa under different wheat straw management after three years from Edwards & Lofty (1979).

Straw management	Population (m^{-2})
Chopped, spread and left (mulched)	28
Baled and removed	18
Burnt in rows	18
Spread and burnt	8

Tisdall (1978) showed that by adding large amounts of straw (68 t ha^{-1}) followed by an annual addition of 5.5 t ha^{-1} populations of mainly megascolecids with some A. caliginosa and others rose to 2000 m^{-2}. This effect was found in a peach orchard where neighbouring orchards only had earthworm populations of 150 m^{-2}.

In New Zealand, Waters (1955b) found that increases in numbers and weights of A. caliginosa occurred two months after flushes in root die-back under pasture. When flushes were exhausted, or physical conditions became unfavourable, numbers and weights declined.

Residue management would appear to affect populations by its impact on total organic matter returns. Also, the rate of decay, related to the size of residue pieces, has an effect on biomass increase which would probably affect future generations.

A field experiment with a history of eight years of continuous wheat at Adair Research Station, near Timaru was sampled for earthworm populations for this thesis. The treatments and results are shown in Table 6.6.

Table 6.6 Earthworm populations under continuous wheat with residue and cultivation treatments.

Cultivation / Residue management	Ploughed	Direct-drilled
Burnt	100 b	320 ab
Mulched	300 ab	630 a
	LSD ($p<0.05$) = 410	

Means NOT sharing letters were significantly different ($p<0.01$).

It is apparent from Table 6.6 that mulching rather than burning of straw residues, and zero tillage rather than ploughing have beneficial effects on earthworm populations. The interactive effect of ploughing and burning residues was significantly more deleterious to earthworm populations compared with mulching and direct-drilling ($p<0.05$).

The results from Edwards & Lofty were shown in Table 6.5. The quotient for Mulched/Burnt from that table is 3.5. The quotient from Table 6.6 for Mulched/Burnt is 3 for ploughed plots and 2 for direct-drilled plots. It might be concluded from this data (cited and original) that over a period of three or more years, a differential of 2 to 3 times the number the number of worms would be found under mulched residue management compared with burning.

6.3.3 Effects of cultivation.

Cultivation influences the temperature, water content, organic matter content and organic matter distribution in soil (Edwards, 1983). Edwards & Lofty (1980) found that an average earthworm population in Britain was 100 to 150 m^{-2}. Of these 10 to 35 m^{-2} were anecic (deep burrowers). Edwards & Lofty also showed that after six years of continuous treatments L. terrestris was between 1.5 and 6.0 times more numerous in direct-drilled (DD) soil compared with ploughed (PL) soil. A. longa, A. caliginosa, and O. cyaneum were 1.1 to 2.6 times more numerous in DD than PL soils. The biomass increases were similar to the numerical increases.

In another experiment (Edwards & Lofty, 1982) anecic worms L. terrestris and A. longa were 17.5 times more numerous in DD than PL soil after eight years. Direct-drilling favoured anecic and epiendogeic worms, but numbers of both cultivation treatments declined under continuous wheat compared with pasture, which was assumed to be an effect of a decline in organic matter. Minimum cultivation had an intermediate effect on populations of anecic species. For endogeic species minimum cultivation had a similar effect to that of ploughing.

In the U.S.A., House & Parmelee (1985) found that a population of A. caliginosa and L. rubellus declined in the years following conversion of pasture to Sorghum cropping with green manuring. However, the decline was far less marked under DD than PL, where the ratio of worms in DD soil to those in PL soil (DD/PL) was 3.5 in one year and 6 the following year.

Further work by Edwards (1983) showed that, under repeated cultivation conditions, high inputs of organic matter favoured the endogeic species A. caliginosa and Allolobophora chlorotica. The first type of worms to decline on the ploughing up of pasture were the anecic species then the endogeic species. The principal reason was found to be organic matter decline rather than mechanical damage. Ploughing, by its very nature, removes litter from the surface and this has a profound effect on obligate surface feeders. L. terrestris was thus worse affected than endogeic species. Interestingly, A. longa was shown not to be an obligate surface feeder even though it is a facultative one. A. longa burrows deep like an anecic worm but can feed as an endogeic worm out of necessity (Edwards & Lofty, 1979).

In a comprehensive survey in England, Barnes & Ellis (1979) showed that numbers were always greater under DD than PL management. The results are shown in Table 6.7 below;

Table 6.7 Comparison of earthworm numbers between direct-drilling and ploughing on a range of soil types from Barnes & Ellis (1979)

Duration of treatment	Approximate DD/PL ratio of earthworm populations	soil series (and texture)
4 years	3	Denchworth (clay)
4 years	4	Evesham (clayey calcareous)
4 years	4	Andover (silt over chalk)
5 years	2	(Sandy loam in winter wheat)
3 years	3	(Sandy loam in spring barley)

Edwards & Lofty (1982) showed that after four years numbers of endogeic species were 3 or 4 times greater in DD than PL soils. They also found that chisel ploughing affected endogeic species such as A. caliginosa as much as ploughing, rather than being intermediate between PL and DD. Edwards & Lofty also considered that although a response to cultivation differences was evident after two years, a steadier state was found after three or four years, taking into account seasonal fluctuations. In 1983, Edwards showed that cultivation by disc, harrow and grubber had an intermediate effect on A. caliginosa compared with PL and DD.

Results of study for this thesis from the tillage and cropping experiment (described in Section 4.1) are shown in Table 6.8. They show that while a clear response to cultivation occurred after two years, there was no significant difference between growing wheat as an annual and Italian ryegrass grown as an annual.

Table 6.8 Earthworm populations of the tillage and cropping experiment after two years.

Cultivation Crop	Ploughed	Direct-drilled
Wheat	360 b	670 a
Italian ryegrass	390 b	570 a
	LSD($p<0.05$) = 160	
	Means NOT sharing letters were significantly different ($p<0.05$).	

From Table 6.6 the quotient for DD/PL = 2.4 after seven years. Table 6.3 shows DD/PL = 1.4 after two years and Table 6.8 shows DD/PL = 1.7 after two years. It may be concluded that experimental results predict an earthworm population between 1.5 and 2.5 times larger under DD than PL after two or more years of treatments.

6.3.4 Other effects on populations

One other important factor affecting earthworm populations is traffic and treading causing puddling and compaction. Low (1972) showed that an earthworm population was halved by an accidental treading event when cattle broke into an experimental area. This sort of effect is much more immediate than cropping, cultivation or residue management history. When anaerobic conditions occur worms often leave the soil and migrate (Martin, 1978). In New Zealand, Waters (1955b) found that poor aeration under high moisture conditions was associated with a decline in weight and numbers.

Sites 25, 35 & 36 of the survey of silt loams received severe compaction by vehicle traffic in wet weather (see Appendix Three). That event reduced populations to about a third their original number (Site 26). On two dairy farm sites (20 & 21) populations were about half of what would be expected given the other management factors. This was probably due to treading damage from repeated over-wintering of heifers on these sites.

Edwards (1980) gave a list of harmful chemical compounds used in plant protection. Fungicides including carbamates, in particular, are deleterious to most earthworms. Nematicides, some organochlorines and a few organophosphates are also toxic. Herbicides are not usually toxic to earthworms. Paraquat and Glyphosate, which are both common broad spectrum herbicides, are notably inoccuous. It was shown by Clements (1982) that long term use of an organophosphorus compound, phorate, caused a decline in earthworm numbers with an associated decline in production in grassland. However, it was shown by McColl (1984) that populations recovered the following year after isolated applications of toxic chemicals that were not repeatedly used.

Long term irrigation at Winchmore, on the Canterbury Plain, was found to favour a larger population of A. caliginosa, L. rubellus and O. cyaneum (Lee, 1959). Under irrigation the minimum soil moisture content was 20 % (w/w) whereas without irrigation the moisture content fell as low as 11 % (w/w). Numbers were 375 m^{-2} under irrigation and 125 m^{-2} without. This work was conducted on a Lismore soil which tends to be droughty (Kear et al., 1967). The effect may, however, have also been associated with increased dry matter production under irrigation.

In this study, only one site was found to have a total absence of worms. A strong northwesterly wind eight years previously had blown the top few millimetres of soil containing a pre-emergent herbicide, "Sinbar" (active ingredient Terbacil), to one side of a field where it became concentrated and had not grown any vegetation since 1980. Under that long term bare fallow (site 39), no earthworms were found.

6.4 SUMMARY OF EARTHWORM POPULATIONS.

Stockdill (1982) found that numbers in New Zealand (predominantly A. caliginosa) were between 500 and 1000 m^{-2} under pasture. He reported a maximum of 2000 m^{-2} under highly favourable conditions. Also in New Zealand, McColl (1984) found maximum numbers of 2100 and 2000 m^{-2} at two sites in the south of the North Island.

Barley (1959a) found 540 m^{-2} of E. rosea and A. caliginosa under pasture and a long ley. In the Netherlands a predominantly A. caliginosa population was 300 to 900 m^{-2} under old grassland with a mean of 500 m^{-2} and a biomass of 2.5 t ha^{-1} (Hoogerkamp et al., 1983). It is important to note from the work of Piearce (1978) that A. longa (anecic) and A. caliginosa (endogeic) grow to quite different sizes. Piearce found that A. longa individuals were on average five times the biomass of A. caliginosa. Beacause New Zealand populations are predominantly A. caliginosa, numbers (m^{-2}) are high, maybe five times higher than the number with the same biomass in Europe, where anecic species predominate. Work from France by Bouché & Gardner (1984) showed that anecic species were about 2.8 times heavier than endogeic species since anecic worms were 52 % of the numbers but 75 % of the biomass. Care must therefore be taken to match European work with New Zealand work by biomass rather than number because of the different sizes of species.

A summary of earthworm populations observed in this study to the nearest hundred is shown in Table 6.9. It is interesting to note that soils with a history of "favourable" management in terms of soil structure showed populations larger than 300 m^{-2}. Those sites which

Table 6.9 Summary of earthworm populations.

Numbers (m^{-2})	No. sites	Governing management history.
>1400		
>1300	(2)	PL and DD ryegrass from pasture.
>1200		
>1100		
>1000		
>900	(1)	DD wheat from pasture.
>800	(2)	DD fallow from pasture; permanent pasture.
>700	(1)	Clover from DD cereals.
>600	(5)	PL wheat from pasture; DD cereals; Meadow pasture (x2); DD wheat from cont. cereals.
>500	(6)	DD cereals; Permanent pasture; stocked lucerne; Fallow from cont. cult. cereals; DD grass from cereals; Clover from dd cereals.
>400	(5)	Grass from DD cereals; Cont. cult cereals; Grass from cont. cult. cereals (x2); Fallow from cont. cult. cereals.
>300	(6)	PL fallow from pasture; Heavy traffic on grass; Clover from cont. cult. cereals; Lucerne (unstocked); PL grass from cont. cult. cereals; PL wheat from cont. cult. cereals
>200	(10)	Grass from cont. cult. cereals (x8); Heavily trodden pasture; Cont. Cult. wheat.
>100	(2)	Heavily trodden pasture; Very heavy traffic.
>0	(3)	Chemical fallow; Very heavy traffic (x2).

might be termed 'abused', which have management systems normally associated with a decline in structural status fell below 300 m^{-2}. Earthworm populations were thus found to be a loose index of favourability of management history.

From the data in Appendix Six it was calculated that, for the spring and summer sampling dates used, the percentage of mature individuals ranged from 0 to 57 %. The average was 17 % mature (clitellate). Compacted sites (20, 21, 25, 26, 35 & 36) were associated with the higher proportions of mature individuals. This may reflect a greater ability of mature worms to adjust to compaction.It has also been calculated that on average 83 % of individuals were A. caliginosa. The values ranged from 50 to 100 %. It is quite clear from this that A. caliginosa dominated the populations observed in this study.

Results for crop effects on populations were inconclusive. Mulching residues compared with burning resulted in a differential population of 2 or 3 times. Direct-drilling compared with ploughing was associated with 1.5 to 2.5 times the earthworm populations. Mulching and residue management may have a larger inpact on populations than cultivation.

Compaction by stock hooves and traffic, and the resulting anaerobic conditions can reduce populations by half, or more drastically. These were rapid responses from which populations may recover in the following year as long as events were not repeated.